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Reference points for the Iberian sardine stock (ICES areas VIIIc and IXa)

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Abstract

Three Yield-Per-Recruit/stock-recruitment approaches (deterministic, stochastic with plotMSY and stochastic with HCS) were used to explore reference points for the management of the Iberian sardine. The sensitivity of reference points was evaluated in relation to alternative scenarios of productivity, growth and selectivity. Growth and selectivity scenarios had a small impact on stock projections whereas productivity scenarios were very influential. The three approaches gave coherent results, but the approach using HCS, assuming uncertainty in stock biology and recruitment dynamics, was preferred to derive reference points for sardine. In this approach, the risks of the stock falling below some low biomass level can also be taken into account. This possibility was considered to be useful in the case of the sardine for which exploitation at maximum YPR or $F_{0.1}$ resulted in values above historical exploitation and higher than F_{loss} , therefore unsuitable as precautionary management targets.

Bloss (306 thousand t) is proposed as a proxy for B_{lim} but given no indication that recruitment is impaired below this biomass level, the group considers that the level of risk of falling below this candidate for B_{lim} acceptable in the evaluation of a management plan should be higher than the standard ICES value (5%). The stock productivity has declined over time; therefore a scenario of low productivity was assumed (recruitment in the period 1993-2010). Under this productivity scenario, the F_{msy} value for the sardine stock is 0.34, a value associated with a high probability (45%) of the biomass falling below the proposed B_{lim} and therefore, incompatible with precautionary considerations. The WG proposes an $F = 0.27$, corresponding to a $Prob(B < B_{lim}) < 15\%$ under equilibrium, as the best available candidate for an F management target (proxy for F_{msy}) assuming the low productivity scenario (since 1993) will continue in the future. This F provides high yield conditional to a low probability that the biomass falls below $B_{lim} = Bloss$ in equilibrium, thus incorporating precautionary considerations.

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1. Introduction

The Iberian sardine stock assessed by ICES covers the Atlantic waters of the Iberian Peninsula (ICES areas VIIIc and IXa), extending from the Strait of Gibraltar in the south to the border with France in the Inner Bay of Biscay in the north.

The historical series of Iberian sardine catches used in the assessment goes back to 1978 and is provided by the national laboratories of both Spain and Portugal. During the last decades, catches have exhibited some fluctuations, peaked in 1981 at 217 thousand t, and thereafter showing a general decrease (Figure 1.1).

An age structured stock assessment model, Stock synthesis 3 (Methot, 2012) is applied since the last benchmark assessment (ICES, 2012a) to fishery dependent and independent data (acoustic and DEPM surveys) to derive estimates of population abundance, recruitment and fishing mortality. Recruitment has extensive variability showing peak values with some regularity (Figure 1.2; Table 1). A time series analysis of recruitment indicated a significant autocorrelation at lag 1 year and cyclical variations of 4-5 years (Santos et al. 2011). Both the level of recruitment and stock productivity (number of recruits per spawner) show a downward trend over time which appears to be partly explained by the environment (Solari et al. 2010; Santos et al. 2012; Figure 1.2, Annex 1). The historical biomass shows extensive variation as well (Figure 1.2; Table 1). The higher levels calculated in the assessment, from the early 1990's, indicate that sardine population may have been more than two times its actual size. This has been routinely observed in pelagic fish populations all around the world showing drastic variations in size, with population crashes and sudden recoveries (Schwartzlose et al, 1999).

Reference points were proposed in the last benchmark assessment for this stock (ICES, 2012a) but were not accepted (see ICES 2012b, Technical minutes of the ADGHANSA). This WD proposes reference points for the management of sardine. Three approaches, deterministic YPR, stochastic YPR with plotMSY and stochastic YPR with HCS, were used to explore reference points. In all cases, YPR analyses were combined with recruitment dynamics. An overview of the literature on environmental effects on sardine recruitment and its trophic role in the ecosystem as well as stock recruitment and reference points for other sardine stocks was undertaken (Annex 1) to support the discussion of approaches and scenarios considered in the present WD.

2. Materials and methods

2.1 Input data

The exploration of reference points was based on data from the last sardine assessment (ICES, 2012b) (see note about F estimates¹). As in ICES (2012b), recruitment (Age 0) estimated in the final year of the assessment, 2011, was not accepted since there is no data from the acoustic survey in the interim year (2012). Therefore, the 2011 recruitment was excluded from the fit of stock recruitment relationships. Moreover, the population at age 1 in the beginning of 2012 was re-calculated.

The initial population is the population at 1 January 2012 estimated in the assessment, except for age 1. Numbers-at-age 1 in the beginning of 2012 were obtained projecting from the geometric mean recruitment in 1993-2010, $RGM(93-10) = 9028$ billion individuals in 2011 with $F_{0,2011}$ and $M_{0,2011}$ (see section 2.1.1) The CVs for numbers at ages 1-6+ were assumed to be equal to the CVs estimated by the assessment model for the 2011 population. Numbers-at-age 0 in 2012 were equal to the $RGM(93-10) = 9028$ billion individuals. A CV=0.5 corresponding to the CV of log recruitment in 1993-2010 was taken.

Natural mortality was assumed to be equal to that in the assessment. Uncertainty to this parameter was not taken into account.

In the last sardine benchmark (ICES, 2012a), it was decided to adopt the biomass of age 1 and older individuals, B_{1+} , as an indicator of spawning biomass for this stock. In this WD, where a maturity ogive needs to be input, a knife-edge ogive with 100% mature at age 1+ with no uncertainty is considered. Moreover, B_{1+} is the reference biomass used for the estimation of stock recruitment relationships and calculation of candidate reference points.

The lowest observed biomass in the stock history, $B_{low}=306$ thousand t, is the estimate of biomass in the year 2000.

As in the assessment, the reference fishing mortality was the mean of ages 2-5, $F(2-5)$.

¹ F-at-age and reference F's reported in WGHANSA 2012 were calculated as $-\ln(N_{a+1,t+1}/N_{a,t})$ minus M from the model estimates of population N-at-age; however, to calculate Z for age 5 (maxage-1), SS3 includes numbers for the 6+ group in the same year, i.e. $-\ln(N_{6,y+1}/(N_{5,y}+N_{6,y}))$. Fs for age 5 and consequently mean $F(2-5)$ are therefore misreported in WGHANSA 2012. For the purpose of this WD, correct Fs for age 5 and reference Fs were calculated multiplying age5-selectivity by apical F by year (Table 1). The correct F-reference is higher than the F-reference in WGHANSA 2012 with differences of 2-7% up to 1990 and 7-18% since 1991.

2.1.1 Scenarios of recruitment

Despite little or no unequivocal evidence of a clear regime shift, at least at a regional scale (Annex 1), the historical stock dynamics suggests sardine productivity has declined over time. The mean productivity of the stock across the whole historical period may not be representative of future productivity. The mean stock productivity in some recent period is a plausible scenario for future stock dynamics.

The selection of a period that represents the current level of productivity is not easy since there is no abrupt shift or clear transition in the time series (Figure 1.2). Nevertheless, the historical series suggests recruitment in approximately the last 20 years is at a lower level than recruitment in the early 20-25 years of the series (Figure 2.1). At the same time a wider range of biomasses is covered in the early than in the recent period. We used a simple regression tree to decide objectively in which year to split the series: this turned out to be 1992. Therefore we selected the period 1993-2010 as representative of current productivity. During this period, recruitment looks approximately stationary (Figure 2.1).

Based on the above productivity periods, two recruitment scenarios are considered in the exploration of reference points:

- Low recruitment: assumes future productivity will be at the level of the recent mean productivity in 1993-2010. The geometric mean recruitment, $RGM(93-10) = 9028$ billion recruits (stochastic projections), or the arithmetic mean recruitment, $RAM(93-10) = 10224$ billion recruits (deterministic projections), are used in the projection of the stock.
- Mean recruitment: assumes future productivity will be at the level of the historical mean productivity in 1978-2010. The geometric mean recruitment, $RGM(78-10) = 12896$ billion recruits (stochastic projections), or the arithmetic mean recruitment, $RAM(78-10) = 15556$ billion recruits (deterministic projections), are used in the projection of the stock.

2.1.2 Scenarios of growth

Historical weights at age show an increase over time. This increase is seen in catch weights since 1991 and in stock weights since 1989 but may have started earlier (in earlier years, fixed weights are used in the assessment; a fixed catch weight of 0.1Kg is used for age 6+). The weight increase is significant for all age groups in the catches and most age groups in the stock (2-4 and 6+) (Figure 2.2). Weight trends might reflect an improve of sardine condition possibly associated to enhanced feeding rate and efficiency induced by temperature noticed since the early 1970s (Silva et al. 2010).

Two scenarios for stock/catch weights-at-age were explored:

- Mean growth: assumes future growth will be equal to historical mean growth. Catch weights-at-age are mean values of 1991-2011 and stock weights-at-age are mean values of 1989-2011. Uncertainty in weights-at-age correspond to the CVs in these periods and therefore include both inter-annual variability and trend.
- High growth: assumes future growth will be equal to mean growth in recent years (as in short term predictions). Both catch and stock weights-at-age are mean values of 2009-2011. CVs were calculated after de-trending the historical series of weights-at-age (since 1991 for catch weights and since 1989 for stock weights). For that, weight was regressed on year separately for each age and CVs were calculated from the residuals scaled to the 2009-2011 mean (Table 2.1). In this case, CVs include only inter-annual variability.

2.1.3 Scenarios of fishery selectivity

In the assessment, fishery selectivity is assumed to vary over time as a random walk in the earlier part of the assessment period, 1978-1990. From 1991 to 2011 selectivity-at-age is fixed over time. The transition between the two periods takes place approximately between 1988 and 1991 and is also made according to a random walk. Age 0 is the reference age and selectivity at ages 4-5 is assumed to be equal to selectivity at age 3.

Younger ages (1-2) and the 6+ group had generally higher selectivity in the earlier than in the recent part of the assessment period (Table 2.2). The opposite is seen for ages 3-5.

Two scenarios of selectivity were considered (Table 2.2):

- Older fish selection: assumes future selectivity will be equal to selectivity in the recent part of the assessment period, 1991-2011

- Younger fish selection: assumes future selectivity will be equal to the mean selectivity in the earlier part of the assessment period, 1978-1987 (excluding the transition phase).

In both scenarios, uncertainty corresponds to the CVs estimated by SS3 (i.e. standard deviations for selectivity parameters on the log scale) and therefore represents the precision of selectivity estimates. For age 0 the CV is assumed to be zero and for ages 4-5 it is assumed to be equal to that of age 3.

2.2 Calculation of candidate reference points

A base case scenario was set up with input data listed in Table 2.3. The base case considers the following recruitment, growth and selectivity scenarios:

- Low recruitment: mean recruitment is RGM (93-10) or RAM(93-10)
- Mean growth: weights-at-age are mean values of 1989-2011(stock) or 1991-2011 (catch)
- Older fish selection: selectivity-at-age is the selectivity in the period 1991-2011

Not all alternative scenarios were used in all approaches to calculate reference points. Moreover, variants of low productivity/recruitment scenarios are explored in the deterministic and HCS projections. Further details on the input data and options are described in the corresponding sections.

2.2.1 Deterministic reference points.

An Excel spreadsheet was designed to carry out deterministic YPR analyses using the input data for the base case scenario. The alternative scenarios of mean recruitment, and high growth were explored (Table below). The sensitivity of reference points relative to a scenario of very poor recruitment was also tested. This scenario, **lowest mean recruitment**, considers the downward trend in productivity is halted but recruitment will remain at the lowest range of the historical series, RGM=6243 billion recruits and RAM=6757 billion recruits. In all cases, both RGM and RAM alternatives were explored.

Case	Scenarios		
	Recruitment	Growth	Selectivity
Base case	Low	Mean	Older fish
Case 1	Low	High	Older fish
Case 2	Mean	Mean	Older fish
Case 3	Mean	High	Older fish
Case 4	Lowest	Mean	Older fish
Case 5	Lowest	High	Older fish

Fishing mortality levels from the YPR analysis (i.e., independent of the recruitment level), F35%B1+, F40%B1+, F50%B1+, F60%B1+ and F0.1 were calculated. Fmed and Floss, as well as their corresponding biomasses, were also considered of interest for the discussion of reference points. Fmed was calculated as the fishing mortality yielding, in the YPR analysis, the B1+/R inverse to the median of the R/B1+ series of pair data points. Floss is the fishing mortality producing Bloss, conditioned to the recruitment geometric or arithmetic mean values of the hypothesis of productivity being tested.

2.2.2 Stochastic YPR using plotMSY

Yield per recruit and MSY reference points and, their associated uncertainties were estimated by means of the plotMSY software (WKMSYREF2013). Estimates of Fmsy were based on the combination of the three common stock recruit relationships: Ricker, Beverton-Holt and Hockey stick (approximated by a continuous function). The software default weighting of the stock recruitment relationships was used. The procedure for weighting by likelihood is to calculate the harmonic mean H_i for each model i using the number of samples given by the number of iterations, then to allocate a weighting to model i as follows: $H_i/\sum_i H_i$. A thousand iterations were output.

Input data are those listed in Table 2.3. Two runs were carried out, one with the base case recruitment scenario (low recruitment) and another one with the mean recruitment scenario.

2.2.3 Stochastic YPR using HCS13_3

Stochastic YPR runs were carried out with the software HCS13_3 (Skagen, 2013). The base case scenario was considered with input data listed in Table 2.3 except that

uncertainty in selectivity-at-age was not taken into account. The stock recruitment function is a Hockey stick with $R_{max}=RGM$ (93-10) and a breakpoint at $B_{loss}= 306$ thousand t. Recruitment was assumed to be log-normally distributed with $\sigma=0.5$. The random noise multiplier on recruitment was constrained to vary between 0.3 and 3 to avoid randomly drawn recruitments outside the range of historical recruitments. This range comes from trials to fit the estimated to the historical recruitment distribution.

The population was projected 98 years with constant fishing mortality (**target F**) in the range 0.0-1.0 and no observation or implementation error.

The software provides mean values and percentiles (10,50,90) of catch, biomass and fishing mortality calculated over all the bootstrap replicas for each target F value in the last year of the projection period.

A risk of $B_{1+} < B_{loss}$ is calculated as the percentage of trajectories where biomass falls below the B_{loss} value in year 98. A risk of crashing the stock ($B_{1+} < 1/10 * B_{loss}$) is calculated as the percentage the percentage of trajectories where biomass falls below $1/10 * B_{loss}$ accumulated over the projection period.

The following statistics were considered to be of interest to discuss candidate reference points:

1. For a probability lower than 5% of B_{1+} being below B_{loss}
 - Mean value and percentiles of the equilibrium fishing mortality
 - Mean value and percentiles of the equilibrium catch (corresponding to F above)
 - Mean value and percentiles of the equilibrium biomass (corresponding to F above)
2. The maximum equilibrium fishing mortality, the corresponding catch and biomass (MSY proxies)

Values of fishing mortality considered in point 1 are related to the maximum fishing mortality which, with high probability, keeps the stock biomass above B_{loss} assuming equilibrium conditions. These are named PSY values (for precautionary and sustainable yield). Values of F below F_{PSY} are associated with a probability of $B_{1+} < B_{loss}$ lower than 5%. For each target F there is a range of realized Fs which reflect uncertainty in input data.

The alternative scenarios considered are summarized in the Table below:

Case	Scenarios			
	Recruitment	HS breakpoint	Growth	Selectivity
Base case a	Low	Bloss=306	Mean	Older fish
	b	Low=250	Mean	Older fish
	c	High=350	Mean	Older fish
Case 2			High	Older fish
Case 3			Mean	Younger fish
Case 4	Mean	Bloss=306	Mean	Older fish

Within the base case scenario, the sensitivity of the reference points to bias in the breakpoint of the stock recruitment model was also tested (Cases 1b and 1c). Options for breakpoints for the Hockey stick take into account uncertainty in Bloss. The base case scenario assumes the breakpoint of the Hockey stick curve is at Bloss since there is no evidence of impaired recruitment below Bloss. The location of the breakpoint is unknown and, depending on the model and software used, can be placed within a wide range of biomasses (e.g. 287 thousand t in FLR, 357 thousand t in plotMSY). Assuming such differences illustrate at least part of the uncertainty in the breakpoint and taking also into account the average CVs of biomass in the assessment (~16%) we compared the base case with alternatives assuming a breakpoint at $Bloss \pm 16\%$.

In case 4 recruitment was assumed to be log-normally distributed with $\sigma=0.62$. This sigma corresponds to the CV of log recruitment in 1978-2010, the period representing the mean productivity scenario.

3. Results

Preliminary work was carried out to explore a range of stock recruitment models using FLR. The results are summarized in Annex 2.

3.1 Deterministic Reference Points

F reference points derived from the YPR curve and corresponding biomass levels conditioned to the low recruitment scenario, RGM(93-10), can be seen in Table 3.1a (F0.1 corresponds to a %B1+ of 37.9%).

The results are consistent with corresponding median F_s produced by plotMSY software (section 3.2 and Table 3.4). F_{max} is not placed within the range of $F_{mult} < 10$ for which the workbook was run so it was perceived to be above 3.3. The plotMSY software pointed out to an F_{max} around 3 (median=2.6). In any case well above any meaningful exploitation rate in terms of credible sustainability. The sensitivity of the F reference points to the high growth scenario (mean 2009-2011) is minimal (Table 3.1b).

F_{loss} conditioned to the geometric mean value of the three recruitment scenarios being tested is presented in Table 3.2 (upper panel). The sensitivity to the use of the arithmetic mean was relevant (table 3.2. middle panel). The sensitivity to the mean weights-at-age was minima (Table 3.2 bottom panel). According to ICES CM 2003/ACFM:15, in order to estimate F_{loss} when no clear S-R relationship can be defined then the arithmetic average of the recruitment for the time series available is a candidate for the recruitment to be expected from the F_{loss} spawning biomass. Therefore from the tables 3.2 those referring to the arithmetic mean (since 1993) are to be preferred for F_{loss} .

For a management seeking to avoid dropping biomass below F_{loss} , then F target should be below F_{loss} . Assuming the recent low productivity of the stock, F_{loss} is 0.51 (regardless of the mean weights being used). This implies that $F_{0.1}$ and all F_{B1+} corresponding to percentages of the virgin biomass below about 43% will not be sustainable in the long term because of being above F_{loss} for the arithmetic mean R . Since F_{loss} is dependent on the average level of recruitment, F_{loss} would be substantially higher in the scenario of historical mean recruitment (at 1.08) and substantially lower (0.20) if the very recent low recruitment scenario (since 2006) would be maintained in the long term.

The median replacement lines for the two scenarios of stock productivity, mean (since 1978) and low (since 1993), have slopes of 0.021 and 0.018 thousands of recruits per kg of B_{1+} , respectively (Figure 3.1). The slope (and therefore productivity) corresponding to the lowest recruitment scenario (since 2006) is very similar to that in the recent period (0.018). The inverse of those replacement lines correspond with B_{1+}/R of 47.7, 54.2 and 54.9 Kg per recruit and correspond with the F_{med} values shown in Table 3.3. The sensitivity of F_{med} to the use of the selected mean weights for the catches and the stock were minima and always below 10%

F_{med} can be considered a sustainable fishing mortality at the average productivity of the stock preventing any clear tendency in the population level, i.e. keeping biomass around the mean of the period of consideration of the stock recruitment relationship.

For this stock F_{med} for the low recruitment scenario (since 1993; 0.11) is well below F_{loss} (0.51) and well below the historical average exploitation of the stock (0.31).

A summary of the results is shown in Figure 3.2.

3.2 Stochastic Reference points with plotMSY

The YPR and Biomass per recruit curves with corresponding quantiles are shown in Figure 3.3. Fishing mortality reference points based on the stochastic YPR model are presented in Table 3.4. B_{msy} and MSY calculated from corresponding per recruit values at F_{max} assuming the low and mean RGM recruitments (named $B_{msy-low/mean}$ and $MSY-low/mean$) are also shown in the table.

The fit of stock recruitment models to data from the low productivity period is shown in Figure 3.4. The number of samples that have feasible parameter estimates for stock recruitment models (i.e. α and β are positive for the usual parameterisation of the functions) was 32 out of 1000 for the Ricker and the Smooth Hockey stick and 21 out of 1000 for the Beverton Holt. The ability to estimate stock recruitment parameters did not improve when data from the mean productivity period, 1978 – 2010, was used (not shown). The mean values of the Hockey stick β (breakpoint of the curve) were estimated to be 357 and 439 thousand t for the low (since 1993) and mean (since 1978) recruitment scenarios, respectively, both with $CV=28\%$.

F_{msy} estimates (50% percentiles) assuming the low recruitment scenario are higher for the Beverton-Holt (0.53) than for the Ricker (0.37) and for the Hockey stick (0.32). The combined F_{msy} estimate (0.39) is intermediate between the Ricker and the Hockey stick estimates and slightly above F_{2010} (0.36) (Table 3.5). Assuming the mean level of recruitment (since 1978), the 50% percentile of F_{msy} is 27% higher than that estimated with the low recruitment scenario.

Overall, candidate reference points explored with plotMSY, both derived from the stochastic YPR analyses ($F_{35\%}$, $F_{40\%}$, $F_{0.1}$, F_{max}), and from the combination of YPR with a stochastic stock recruitment model (F_{msy}), are at the upper limit or above the historical range of fishing mortalities for the stock (see Table 1). Recent studies on low trophic level stocks recommend target fishing mortalities corresponding to percentages of virgin biomass higher 40% (Smith et al. 2011; Horbowy and Luzeńczyk 2012). For LTL species considered as key species in the ecosystem, this percentage

could be as high as 75%B0. Sardine is an important prey species in the pelagic ecosystem. Preliminary results indicate that major sardine predators such as the common dolphin appear to adapt to changes in the abundance of sardine in the ecosystem (Annex 1). However, the trophic role of sardine in the ecosystem (key or non-key species) is still uncertain. Nevertheless, F values around F60%B1+ calculated in this WD (deterministic analysis) seem to be relatively consistent with the fishing mortality that will keep the probability of the stock B1+<Bloss below 5% (see section 3.3).

3.3 Stochastic YPR with HCS13_3

Table 3.6 presents the results for all cases explored with HCS. The equilibrium yield and biomass plots for the base case are shown in Figure 3.5.

Fmsy for the base case scenario is 0.34 corresponding to MSY= 82 thousand t and B1+=326 thousand t. At this fishing mortality level, the risk that B1+ is below Bloss is 45%. The risk is high ($\geq 27\%$) in all alternative scenarios.

In the base case scenario, the maximum fishing mortality (F_PSY) that will keep the probability of B1+<Bloss below 5%, assuming equilibrium, is in the range 0.20-0.24 (median= 0.22) with corresponding yield in the range 54-90 thousand t (median=69). At this level of F the stock will fluctuate in the range 322-540 thousand t (median=414) being therefore at a relatively safe distance above Bloss. The distribution of modeled recruitments fits the distribution of historical recruitments generally well (Figure 3.6). However, high recruitment levels corresponding to recruitment pulses which occurred with some regularity in the past are less frequent in the modeled distribution than suggested in historical data.

The F corresponding to Bloss in this analysis is 0.35 (corresponding to about 52%B1+ for the recent mean weights) This Floss value is slightly below the Floss calculated deterministically with the geometric mean recruitment (=0.40).

Figure 3.7 plots the PSY values for cases 1-3. The impact of bias in the breakpoint of the Hockey stick model was relatively small providing median F_PSY values of 0.20 (high breakpoint) and 0.22 (low breakpoint). As in the deterministic approach, the

impact of assuming alternative scenarios of growth (high growth) and selectivity (selection of younger fish) on F_{PSY} values were also small (Table 3.6).

On the contrary, as seen in the other approaches, the effect of assuming the mean recruitment scenario is substantial: compared to the base case, the 50% percentile of F_{PSY} and $Yield_{PSY}$ double while the corresponding $B1+$ slightly improves (Table 3.6).

4. Discussion and CONCLUSION

The major challenges in the definition of reference points for sardine are the lack of information about biomass levels leading to impaired recruitment (Figure 2.1), the absence of a maximum in the yield per recruit curve within plausible fishing mortality levels (Figure 3.3) and changes in stock productivity over time (Figure 3.1). In this WD, we demonstrated how these aspects influence F reference points which are commonly adopted for the management of fish stocks.

Historical stock- recruitment estimates provide no indication of a biomass level below which recruitment is impaired which conforms to the strict concept of $Blim$. Recruitment dynamics below $Bloss$ are unknown (the general $Blim$ concept).

Given no indication of impaired recruitment below $Bloss$, this point could be taken as Bpa according to ICES guidelines (2003, 2011). ICES states that $Bloss$ may be considered a proxy for Bpa in cases where the dynamic range of SSB in the stock-recruitment plot is narrow and the stock is lightly exploited. However, “narrow range” and “lightly exploited” have not been quantified and decisions should be made case by case (ICES, 2003). The sardine assessment covers 66% of the biomass range and the mean exploitation since 1993 (F_{2-5})=0.29 has been below natural mortality (M_{2-5})=0.36) and F_{loss} =0.35. Therefore, the adoption of $Bloss$ as a proxy for $Blim$ or Bpa is debatable.

However, there are some points of concern about recruitment dynamics, such as some downward trend over time, with indication of lower productivity since 1993 and persistent low recruitments in the last years (since 2006). For these reasons, the group considers $Bloss$ =306 thousand t may be a candidate to evaluate the risk of the stock entering an uncertain biomass dynamic region (so as proxy for $Blim$). Nevertheless the group acknowledges the poor scientific basis for taking it as an inflection point leading to impaired recruitment dynamics. For this reason the risk of falling below this candidate for $Blim$ value may deserve ad hoc considerations and/or consultation with

managers and stakeholders. If needed, F_{lim} could be derived from $F_{loss}=0.35$, the equilibrium fishing mortality producing B_{loss} in the low productivity scenario.

F reference points obtained by the different approaches were generally consistent. Stochastic approaches are preferred since uncertainty in stock biology, selectivity and most importantly, in recruitment dynamics, is taken into account and reflected on reference points. In plotMSY, uncertainty in the form of the stock recruitment relationship can be taken into account and F_{msy} obtained combining common SR models (Ricker, Beverton-Holt and Hockey stick) according to their fit to the data. However, for stocks with no clear stock recruitment relationship such as sardine, different models provide similarly uncertain fits and their combination does not improve the stock recruitment analysis. In HCS, the risks of the stock falling below some low biomass level can be taken into account in the stochastic YPR/stock-recruitment analysis. Thus, precautionary considerations can be added to the derivation of reference points. The group considers this approach to be useful in the case of the sardine for which exploitation at maximum YPR does not seem to be an appropriate management target.

As seen in all approaches, the assumed productivity/recruitment scenario is very influential in stock projections. In the HCS approach, the F target providing the highest yield conditional to a low (<5%) probability that the stock declines below B_{loss} is 0.42 when the complete historical mean productivity scenario (since 1978) is assumed and 0.22 when the low productivity scenario (since 1993) is assumed. On the other hand, the assumption of a very poor recruitment (since 2006) in the deterministic approach resulted in $F_{loss}=0.21$.

Given evidence that stock productivity has declined over time, we considered a scenario where future productivity will be low, i.e. future recruitment will be, on average, at the level of the recruitments since 1993. This scenario, could arise if sardine productivity is associated with a persistent environmental change such as global warming. While such an association is uncertain (Annex 1) the relatively long phase of low productivity advises the adoption of a more conservative scenario instead of a scenario consistent with the mean historical productivity since 1978. The fact that high recruitments occurring in the period 1978-1992 are not appearing in similar frequency or strength since 1993 suggests that average fishing mortalities should require accommodation to this lower productivity of the stock, even if this productivity is largely environmentally driven.

The F_{msy} value obtained for the sardine stock, assuming a low productivity scenario, is 0.34 (Table 3.6) corresponding to a yield of 82 thousand t. This F level seems to provide an optimistic perception of a sustainable harvest level which is incompatible with precautionary considerations. In fact, this F level is associated with a high probability (45%) of the biomass falling below B_{loss} (Table 3.6; Figure 3.5) in equilibrium conditions for the assumed low productivity of the stock.

Conditioning the derivation of a sustainable F by the $\text{Prob}(B < B_{lim})$ allows the derivation of a level consistent with precautionary considerations. The assumption of a $P(B < B_{lim}) < 5\%$ (corresponding to $F = 0.22$), the ICES standard value when there is no alternative indication from managers and stakeholders, would be too stringent in this case given that there is no indication of impaired recruitment at B_{loss} and there is large uncertainty about the interpretation of B_{loss} as B_{lim} or B_{pa} . The group considered that a level of risk = 15% could be acceptable to conciliate precautionary considerations with high sustainable yield (Table 3.7) given the current uncertainties on the meaning of B_{loss} . In fact, if B_{loss} would have been used as B_{pa} , an F_{pa} with a risk of leading below B_{pa} at the 10-25% percentiles would have been considered appropriate according to ICES 2001 guidelines (ICES 2001).

The F corresponding to a $\text{Prob}(B < B_{lim}) < 15\%$ is 0.27 (range 0.24-0.30) and provides a yield of 77 thousand t (range 59-101 thousand t). At this level of F the biomass will fluctuate around 387 thousand t (range 286-501) being therefore at a safe distance above B_{lim} . $F = 0.27$ is close but below the mean of 1993-2011 (0.29), a period when the biomass has fluctuated at a low level but showed no trend and lower than the historical mean (0.31, 1978-2010). This value is halfway in the range from the stringent $F = 0.22$ to the $F_{msy} = 0.34$. Moreover, an $F = 0.27$ should allow recovering the biomass in 5 years if it falls below B_{lim} , with a certainty of ~94% (Table 3.8).

In conclusion, the group considers that $F = 0.27$ it is the best available candidate for an F management target (proxy for F_{msy}) assuming the low productivity scenario (since 1993) will continue in the future. This F provides high yield conditional to a low probability that the biomass falls below $B_{lim} = B_{loss}$ in equilibrium, thus incorporating precautionary considerations.

We note that the generation of recruitments in the stochastic modeling seems to reflect high recruitments in slightly less frequency than observed since 1993. In the past, the sardine stock has produced strong recruitments with some regularity (cycles of 4-5 years, Santos et al. 2011). These recruitments have had a key role in the dynamics of the stock raising the stock biomass 30-90% in the two following years and operating as a rescue when the stock is at a low level. However, intervals between high recruitments have been variable (3-8 years); and no strong recruitment has been observed since 2005. The historical series may not be sufficiently long to correctly quantify their frequency. The way recruitment has been simulated, might have been a bit cautious in comparison with the average productivity in the period 1993-2010. The proposed Fmsy corresponds to a low productivity scenario where good year classes are assumed to be a bit scarcer than in the past 18 years. Therefore, this Fmsy needs to be re-evaluated in some years as further information on recruitment dynamics and stock productivity becomes available. These considerations should also be taken into account in the evaluation of harvest control rules for the stock.

References:

- Horbowy, J., Luzeńczyk, A. 2012. The estimation and robustness of Fmsy and alternative fishing mortality reference points associated with high long-term yield. *Can. J. Fish. Aquat. Sci.* (accepted)
- ICES 2001. Report of the study group on the further development of the precautionary approach to fishery management .ICES Headquarters.2–5 April 2001. ICES CM 2001/ACFM:11.
- ICES 2003. Report of the Study Group on Precautionary Reference Points for Advice on Fishery Management. ICES Headquarters. 24–26 February 2003. ICES CM 2003/ACFM:15.
- ICES. 2012a. Report of the Benchmark Workshop on Pelagic Stocks (WKPELA 2012), 13–17 February 2012, Copenhagen, Denmark. ICES CM 2012/ACOM:47. 572 pp
- ICES. 2012b. Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA), 23 - 28 June 2012, Azores (Horta), Portugal. ICES CM2012/ACOM:16. 544pp.
- Methot Jr., R.D., Wetzel, C.R., 2012. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. *Fish. Res.*
<http://dx.doi.org/10.1016/j.fishres.2012.10.012>
- Santos, M.B., González-Quirós, R., Riveiro, I., Cabanas, J.M., Porteiro, C. and Pierce, G.J., 2012. Cycles, trends and residual variation in the Iberian sardine (*Sardina pilchardus*) recruitment series and their relationship with the environment. *ICES Journal of Marine Science*, 69: 739–750.

Silva, A., Faria, S. , Nunes, C. Changes in sardine maturation since the mid 20th century : can environmental and genetic effects be disentangled ? ICES CM 2010/M :28 : Poster.

Schwartzlose, R.A., Alheit, J., Bakun, A., Baumgartner, T.R., Cloete, R., Crawford, R.J.M., Fletcher, W.J., Green-Ruiz, Y., Hagen, E., Kawasaki, T., Lluch-Belda, D., Lluch-Cota, S.E., MacCall, A.D., Matsuura, Y., Nevárez-Martínez, M.O., Parrish, R.H., Roy, C., Serra, R., Shust, K.V., Ward, M.N. and Zuzunaga, J.Z., 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. South African Journal of Marine Science 21(1), pp. 289-347.

Skagen, D. 2013. HCS program for simulating harvest control rules. Program description and instructions for users. Version HCS13_3. April 2013. Available at www.dwsk.net.

Smith AD, Brown CJ, Bulman CM, Fulton EA, ..., Marzloff M, Shannon LJ, Shin YJ, Tam J. Smith AD, Brown CJ, Bulman CM, Fulton EA, Johnson P, Kaplan IC, Lozano-Montes H, Mackinson S, Marzloff M, Shannon LJ, Shin YJ, Tam J. 2011. Impacts of fishing low-trophic level species on marine ecosystems. Science. 333(6046):1147-50.

Solari, A. P., Santamaría, M. T. G., Borges, M. F., Santos, A. M. P., Mendes, H., Balguerías, E., Díaz Cordero, J. A., Castro, J. J., and Bas, C. 2010. On the dynamics of *Sardina pilchardus*: orbits of stability and environmental forcing. – ICES Journal of Marine Science, 67: 1565–157.

Table 1 – Summary of the sardine stock assessment in 2012 (ICES 2012b)

Year	Biomass 1+	SSB	CV SSB	Recruits Billion individuals	CV		F (2-5)	Apical F	CV		Landings
	'1000 t	'1000 t	%		Recruitment	%			apicalF	%	
							year-1	year-1			'1000 t
1978	424	407	17	23921	15	0.37	0.37	0.46	16		146
1979	464	433	16	27481	15	0.36	0.36	0.44	16		157
1980	560	525	15	31471	14	0.36	0.36	0.43	15		195
1981	659	618	14	19690	17	0.35	0.35	0.41	15		217
1982	667	642	14	10956	23	0.34	0.34	0.38	15		207
1983	572	558	16	49222	11	0.34	0.34	0.36	15		184
1984	734	669	14	15381	18	0.33	0.33	0.36	15		206
1985	781	761	13	14228	18	0.29	0.29	0.30	12		208
1986	677	659	13	11676	19	0.32	0.32	0.33	14		187
1987	584	569	14	23745	13	0.35	0.35	0.36	15		178
1988	555	524	14	13148	17	0.35	0.35	0.36	18		162
1989	545	528	14	12676	17	0.32	0.32	0.33	19		141
1990	492	475	15	13119	17	0.40	0.40	0.41	18		149
1991	475	453	16	36404	11	0.34	0.34	0.37	17		133
1992	759	680	13	26193	12	0.25	0.25	0.27	17		130
1993	898	853	13	11694	15	0.25	0.25	0.28	17		142
1994	809	778	13	10038	14	0.22	0.22	0.24	15		137
1995	818	792	13	7366	14	0.21	0.21	0.23	15		125
1996	549	537	14	11478	12	0.27	0.27	0.29	16		117
1997	483	458	15	6864	14	0.34	0.34	0.37	15		116
1998	397	379	16	9057	13	0.39	0.39	0.42	16		109
1999	363	343	17	7427	15	0.36	0.36	0.39	17		94
2000	306	297	17	22968	12	0.32	0.32	0.35	18		86
2001	453	413	16	13861	13	0.31	0.31	0.34	18		102
2002	513	471	15	7685	15	0.26	0.26	0.28	19		100
2003	462	448	16	5871	18	0.24	0.24	0.27	18		98
2004	442	432	17	26221	11	0.26	0.26	0.29	18		98
2005	520	407	17	9707	14	0.26	0.26	0.28	19		97
2006	581	556	15	3341	18	0.22	0.22	0.24	18		87
2007	537	525	15	5594	16	0.22	0.22	0.24	16		96
2008	412	405	18	7511	17	0.31	0.31	0.34	18		101
2009	336	323	19	11431	18	0.32	0.32	0.35	22		87
2010	314	294	21	5910	22	0.36	0.36	0.40	23		90
2011	330	330	22	11627	31	0.31	0.31	0.34	25		80
Mean 1978-2011	543	516	15	15440	16	0.31	0.31	0.34	17		134
Minimum 1978-2011	306	294	13	3341	11	0.21	0.21	0.23	12		80
Maximum 1978-2011	898	853	22	49222	31	0.40	0.40	0.46	25		217
Mean 1993-2011	501	476	16	10297	16	0.29	0.29	0.31	18		103
Minimum 1993-2011	306	294	13	3341	11	0.21	0.21	0.23	15		80
Maximum 1993-2011	898	853	22	26221	31	0.39	0.39	0.42	25		142

Table 2.1 – Input values for the growth scenarios: mean weights at age in the stock (a) and in the catch (b) for the whole period (mean growth scenario) and for the recent period (high growth scenario).

(a) Stock weights

Age	Whole period (1991-2011)		Trend over time		Recent period (2009-2011)	
	Mean	CV	Slope	Significance	Mean	CV
				(p-value)		
1	0.024	0.24	-9.09E-05	0.665	0.021	0.26
2	0.043	0.13	4.74E-04	0.014	0.048	0.10
3	0.056	0.09	5.27E-04	0.001	0.059	0.07
4	0.065	0.08	3.23E-04	0.066	0.065	0.07
5	0.070	0.08	7.92E-05	0.689	0.066	0.08
6	0.081	0.16	-1.14E-03	0.009	0.071	0.15

(b) Catch weights

Age	Whole period (1989-2011)		Trend over time		Recent period (2009-2011)	
	Mean	CV	Slope	Significance	Mean	CV
				(p-value)		
0	0.023	0.18	3.42E-04	0.004	0.023	0.14
1	0.041	0.13	4.74E-04	0.003	0.044	0.10
2	0.057	0.10	5.72E-04	0.000	0.063	0.06
3	0.066	0.08	7.20E-04	0.000	0.074	0.04
4	0.072	0.08	6.84E-04	0.000	0.079	0.05
5	0.077	0.07	5.32E-04	0.001	0.081	0.05
6	0.100	-	-	-	0.100	0.10

Table 2.2 – Input data for the two selectivity-at-age scenarios: older fish selection (mean of 1991-2011) and younger fish selection (mean of 2009-2011).

Age	Selectivity		
	1991-2011	1978-1987	CV
	Mean	Mean	
0	0.116	0.104	0
1	0.352	0.480	0.09
2	0.663	1.000	0.09
3	1.000	0.865	0.10
4	1.000	0.865	0.10
5	1.000	0.865	0.10
6	0.366	0.551	0.27

Table 2.3 – Input data for the base case scenario.

Age	Population		Natural mortality	Maturity	Stock weights		Catch weights		Selectivity	
	Number	CV			Mean	CV	Mean	CV	Mean	CV
0	9028	0.50	0.8	0	0.000	0	0.023	0.18	0.116	0
1	3898	0.23	0.5	1	0.024	0.24	0.041	0.13	0.352	0.09
2	1363	0.20	0.4	1	0.043	0.13	0.057	0.10	0.663	0.09
3	1390	0.23	0.3	1	0.056	0.09	0.066	0.08	1.000	0.10
4	472	0.28	0.3	1	0.065	0.08	0.072	0.08	1.000	0.10
5	184	0.34	0.3	1	0.070	0.08	0.077	0.07	1.000	0.10
6	612	0.39	0.3	1	0.081	0.16	0.100	0.10	0.366	0.27

Table 3.1 –F reference points from the deterministic YPR analysis, for the base case scenario (with RGM(1993-2010) (a). Table (b) shows the sensitivity to the use of recent weights-at-age.

(a)

Reference F	Biomass1+	FMult	Fbar(2-5)	Landings	Yield/R
F60% B1+	389	0.71	0.23	69	7.6
F50% B1+	324	1.07	0.36	85	9.4
F40% B1+	259	1.66	0.55	100	11.1
F35%B1+	227	2.12	0.71	108	11.9
F0.1	246	1.83	0.61	103	11.4

(b)

Reference F	Biomass1+	FMult	Fbar(2-5)	Landings	Yield/R
F60% B1+	374	0.76	0.25	78	8.6
F50% B1+	312	1.15	0.38	95	10.6
F40% B1+	250	1.77	0.59	112	12.4
F35% B1+	219	2.26	0.75	119	13.2
F0.1	169	1.84	0.61	78	12.5

Table 3.2 – Floss from the deterministis YPR analysis for the three recruitment scenarios and two growth scenarios: Upper panel for the geometric mean recruitment (mean weights since 1993), middle panel for the Arithmetic mean recruitment with mean weights since 1993 and bottom panel for the Arithmetic mean recruitment with mean weights since 1996.

Mean Weights earlyNineties-2011		Floss			
Recruitment series	Biomass1+	Fbar(2-5)	Landings	Yield/R	%B1+
GeomMean(1978-2010).Rec.	306,123	0.7812	157,474	12.2111	33.1%
GeomMean(1993-2010).Rec.	305,915	0.4006	89,373	9.8990	47.2%
Geom.Mean since 2006.Rec.	305,985	0.1642	38,278	6.1313	68.3%

Mean Weights since earlyNineties		Floss			
Recruitment series	Biomass1+	Fbar(2-5)	Landings	Yield/R	%B1+
Arithm.Mean(1978-2010).Rec.	306,024	1.0854	203,444	13.0785	27.4%
Arithm.Mean(1993-2010).Rec.	305,996	0.5103	110,658	10.8239	41.7%
Arithm.Mean since 2006.Rec.	306,199	0.2061	47,849	7.0810	63.1%

Mean Weights 2009-2011		Floss			
Recruitment series	Biomass1+	Fbar(2-5)	Landings	Yield/R	%B1+
Arithm.Mean(1978-2010).Rec.	306,071	1.0738	220,946	14.2037	28.5%
Arithm.Mean(1993-2010).Rec.	305,838	0.5086	120,724	11.8084	43.3%
Arithm.Mean since 2006.Rec.	305,885	0.1978	50,743	7.5092	65.5%

Table 3.3 – Fmed from the deterministis YPR analysis for the three recruitment scenarios: Upper panel for the mean growth and bottom panel for high growth scenario.

Mean Weights earlyNineties-2011		F med				
Recruitment series	Biomass1+	FMult	Fbar(2-5)	Landings	Yield/R	%B1+
GeomMean(1978-2010).Rec.	615,672	0.535	0.178	83,299	6.5	66.5%
GeomMean(1993-2010).Rec.	489,964	0.345	0.115	42,940	4.8	75.6%
Geom.Mean since 2006.Rec.	342,493	0.33	0.110	28,715	4.6	76.4%

Mean Weights 2009-2011		Fmed				
Recruitment series	Biomass1+	FMult	Fbar(2-5)	Landings	Yield/R	%B1+
GeomMean(1978-2010).Rec.	608,518	0.525	0.175	89,416	6.9	68.3%
GeomMean(1993-2010).Rec.	490,201	0.31	0.103	42,906	4.8	78.5%
Geom.Mean since 2006.Rec.	342,563	0.295	0.098	28,545	4.6	79.4%

Table 3.4 – F reference points from the stochastic YPR analysis with plotMSY. Bmsy and MSY are calculated from the per recruit values at Fmax for the low and the mean recruitment scenarios.

	F35	F40	F01	Fmax	Bmsy-low	MSY-low	Bmsy-mean	MSY-mean
Deterministic	0.71	0.56	0.61	3.00	290	93	414	133
Mean	0.74	0.57	0.57	2.56	352	80	503	114
5%ile	0.55	0.44	0.47	2.03	277	39	396	55
25%ile	0.63	0.50	0.52	2.41	313	74	447	105
50%ile	0.72	0.56	0.56	2.55	336	82	479	118
75%ile	0.81	0.62	0.60	2.78	379	91	541	130
95%ile	1.09	0.81	0.70	2.95	496	104	709	149
CV	0.22	0.20	0.13	0.12				

Table 3.5 –Fmsy and Fcrash from plotMSY analyses for the two recruitment scenarios.

Percentage	Low R scenario		Mean R scenario	
	Fmsy	Fcrash	Fmsy	Fcrash
5%	0.20	0.22	0.20	0.29
25%	0.28	0.40	0.32	0.50
50%	0.39	0.76	0.48	0.88
75%	0.54	2.02	0.68	1.88
95%	0.87	3.94	1.08	4.14

Table 3.6 – Results of the scenarios considered in the stochastic YPR analysis with HCS. The exact values of the Prob(B1+<Bloss) are shown for each scenario.

Case	R scenario	HS breakpoint	F_PSY			B1+_PSY				Yield_PSY				Risk to Bloss at F_PSY	Fmsy	Bmsy	MSY	Risk to Bloss at Fmsy
			10%	50%	90%	mean	10%	50%	90%	mean	10%	50%	90%					
Base case a		306	0.20	0.22	0.24	426	322	414	540	71	54	69	90	5.4	0.34	326	82	44.5
b		250	0.20	0.22	0.24	428	325	417	540	71	55	70	90	4.8	0.46	291	96	61.2
c		350	0.18	0.20	0.22	436	327	425	554	66	50	65	84	6.1	0.26	365	71	26.7
Case 2	Low	306	0.20	0.22	0.23	435	327	423	554	77	59	75	98	5.0	0.36	328	91	44.4
Case 3		306	0.16	0.18	0.20	436	331	425	549	69	53	68	88	4.2	0.28	339	83	38.0
Case 4	Mean	306	0.37	0.42	0.47	467	332	445	632	143	104	138	190	4.9	0.60	369	154	32.9

Table 3.7 –Detailed results of the base case scenario in the stochastic YPR analysis with HCS.

Target F	Cmean	C10	C50	C90	F10	F50	F90	Bmean	B10	B50	B90	Risk to Blim (%)	Risk of stock crash (%)
0.20	67	52	66	85	0.18	0.20	0.22	443	337	431	557	3	0
0.22	71	54	69	90	0.20	0.22	0.24	426	322	414	540	5	0
0.24	74	57	73	95	0.22	0.24	0.26	410	308	398	524	9	0
0.26	77	59	76	99	0.23	0.26	0.29	395	294	384	510	13	0
0.27	78	59	77	101	0.24	0.27	0.30	387	286	375	501	15	0
0.28	80	60	78	103	0.25	0.28	0.31	380	277	367	492	18	0
0.30	81	60	80	105	0.27	0.30	0.33	363	265	352	475	25	0
0.32	82	59	81	108	0.29	0.32	0.36	346	246	336	460	35	0
0.34	82	56	81	110	0.30	0.34	0.38	326	219	321	443	45	0
0.36	80	49	80	111	0.32	0.36	0.40	304	183	299	425	53	0.1

Table 3.8 – Probability of recovery of the biomass within 5 years when dropping below the breakpoint. All cases where the SSB dropped below the breakpoint are considered, and the percentage of those cases where SSB was above the breakpoint 5 years late is recorded.

F	Percent after 5 years
0.10	100
0.12	100
0.14	100
0.16	100
0.18	99
0.20	99
0.22	98
0.24	97
0.26	95
0.28	93
0.30	91
0.32	88
0.34	85
0.36	82
0.38	78
0.40	75
0.42	71

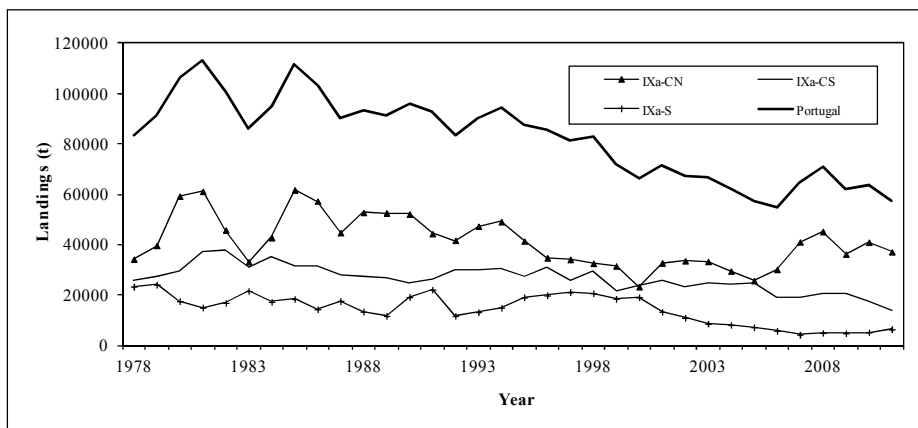
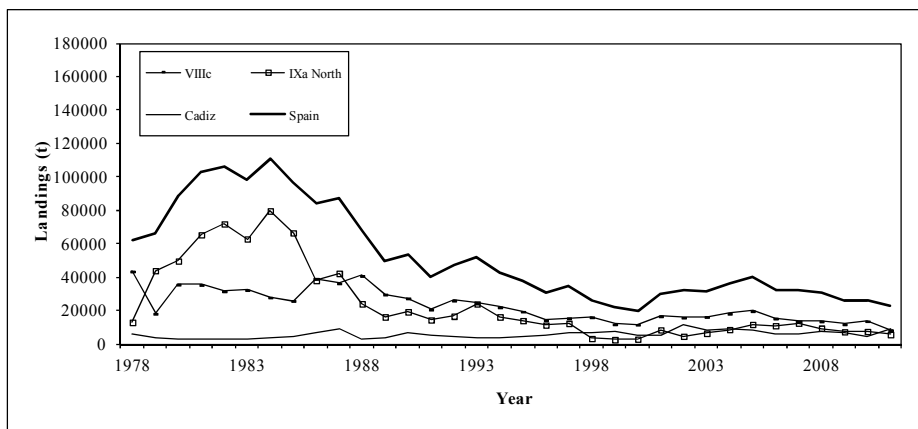
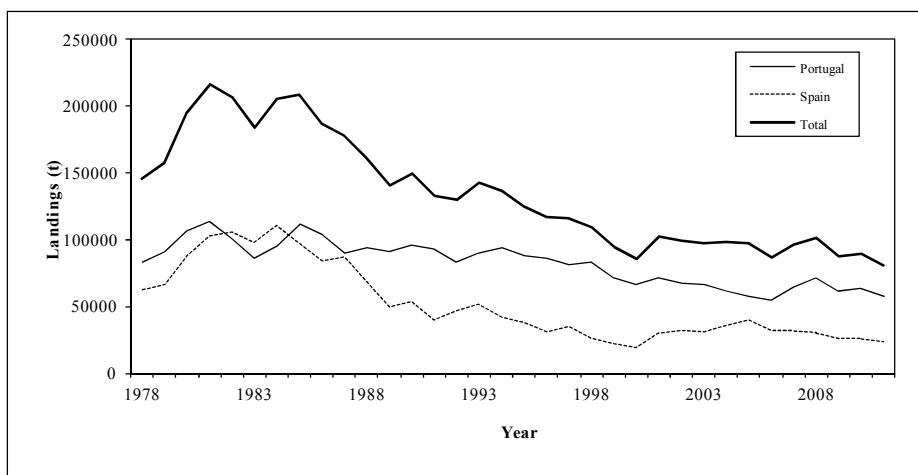
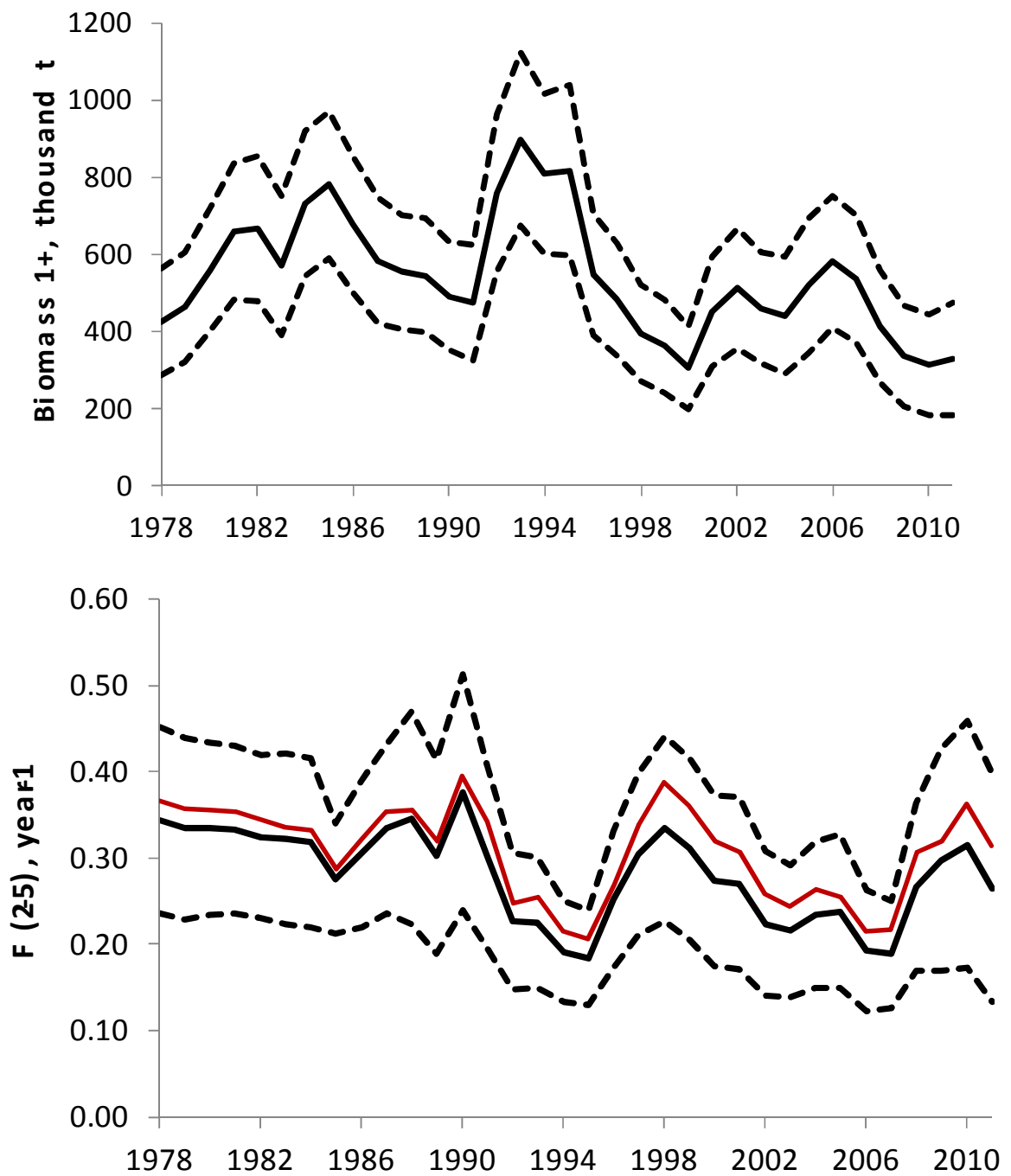


Figure 1.1 – Sardine landings in 1978 – 2011.



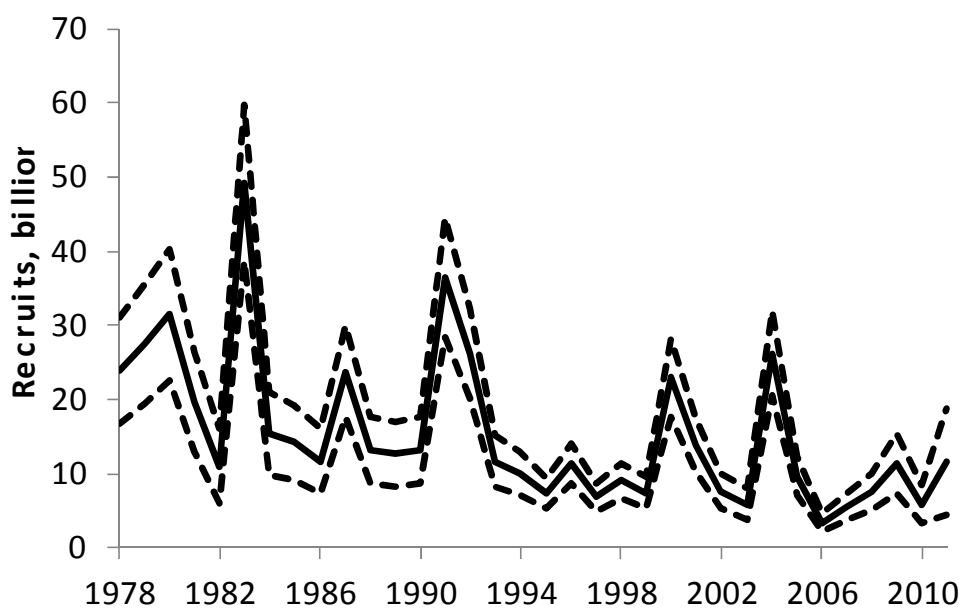


Figure 1.2. Sardine VIIIc and IXa: Historical B1+ (top), F(2-5) (middle) and recruitment (bottom) trajectories in the period 1978 – 2011 (ICES, 2012b). Dashed lines show mean values ± 2 Standard Deviations. The red line shows the corrected F(2-5) series (see footnote 1 and Table 1).

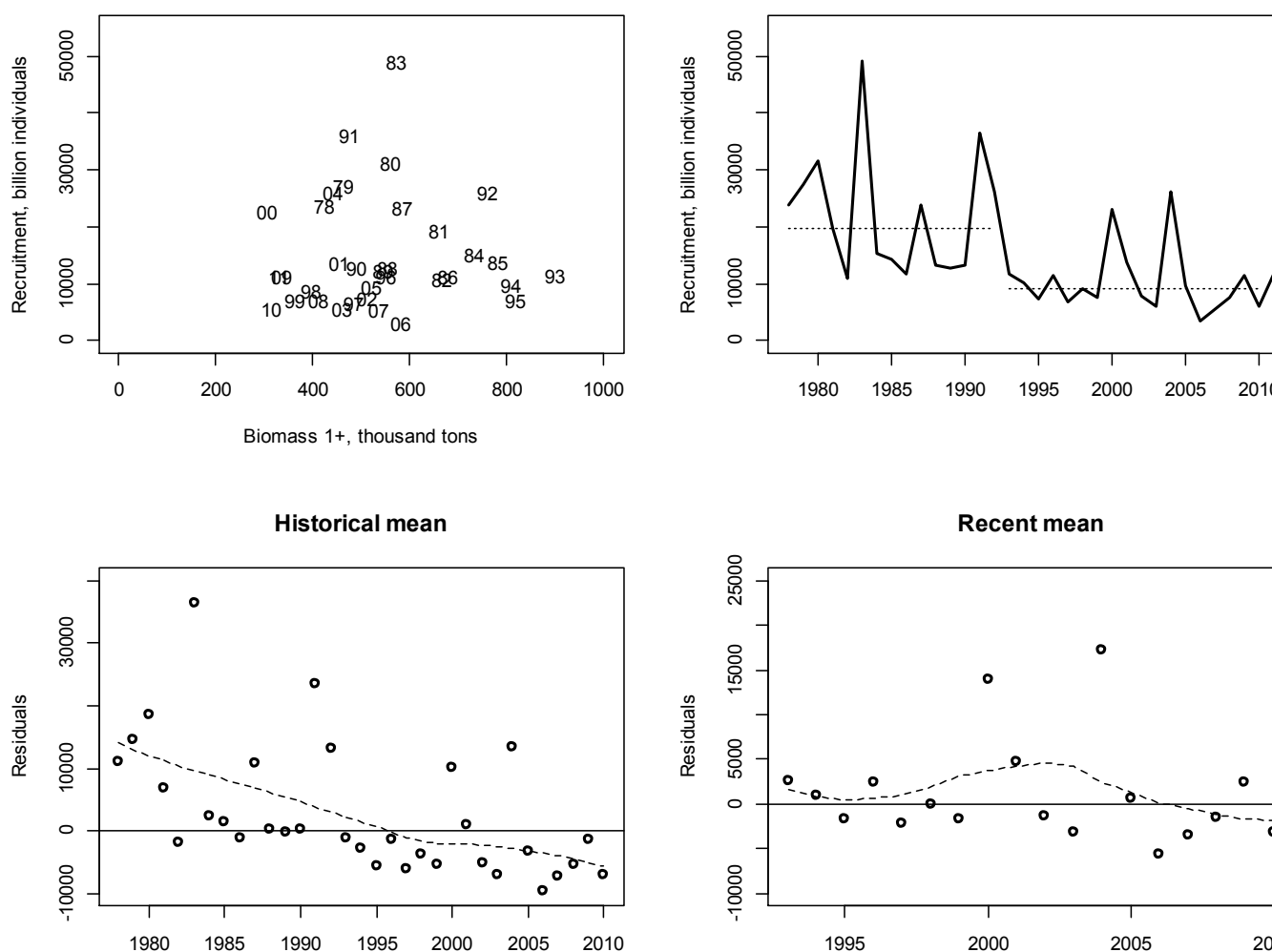


Figure 2.1 – Stock recruitment scatterplot (top left; numbers show years), historical recruitment (top right; dashed lines show geometric mean recruitment in 1978-1992 and 1993-2010 to outline periods with high and low productivity), recruitment deviations from the geometric mean of 1978-2010 (bottom left) and recruitment deviations from the geometric mean of 1993-2010 (bottom right; dashed lines are loess smoothers with span=0.75).

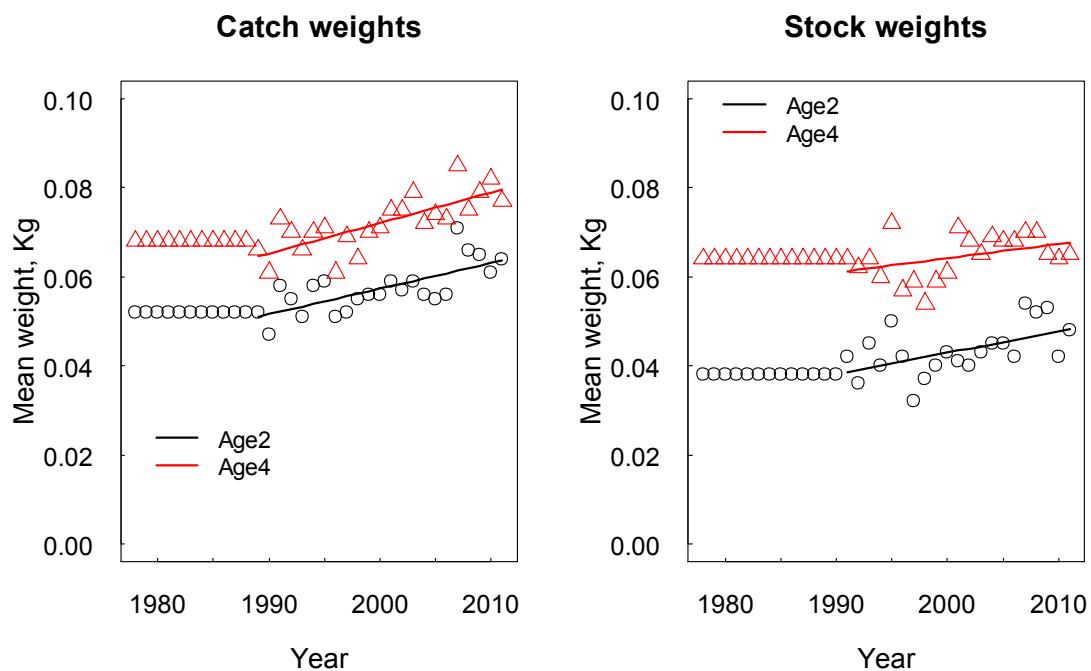


Fig 2.2 – Illustration of trends in weights-at-age. The lines are linear regressions of weight on year for each age.

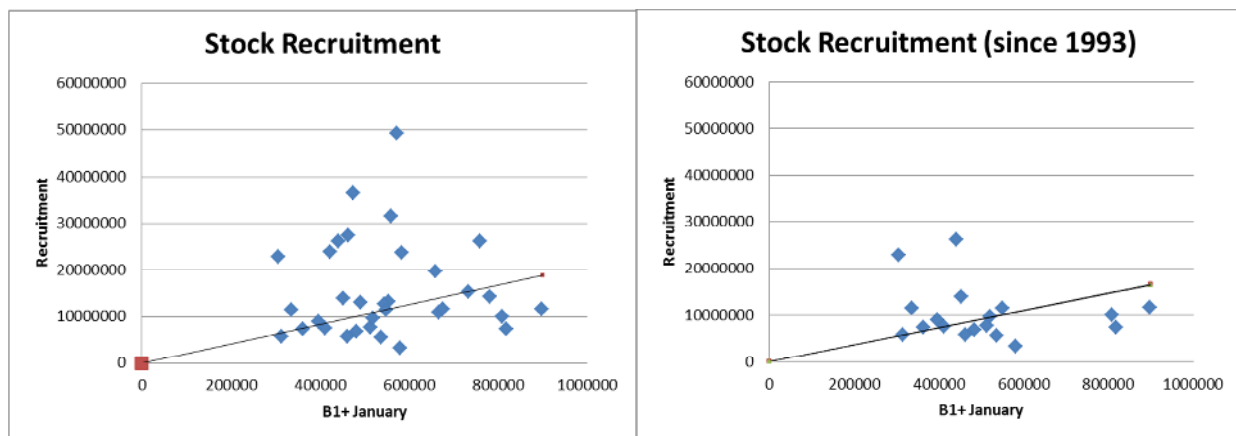


Figure 3.1 – Stock recruitment scatterplots for the periods 1978-2010 (left) and 1993-2010 (right) with the median replacement lines.

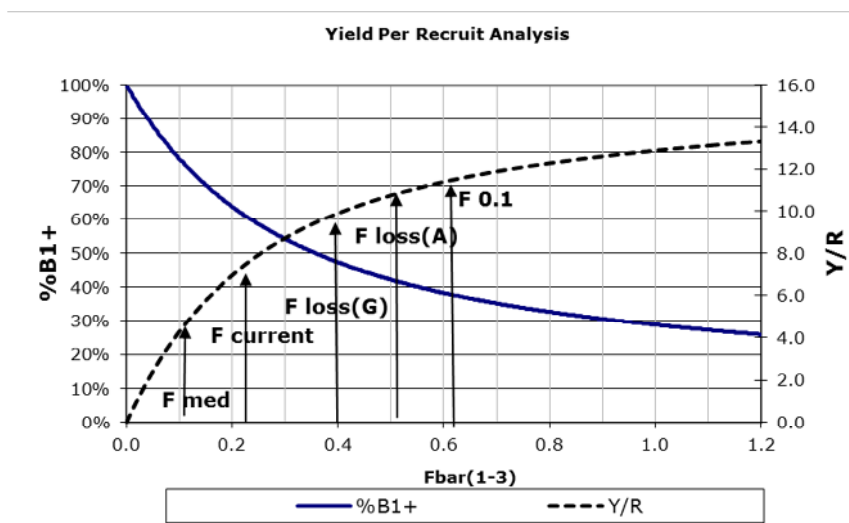


Figure 3.2 - Summary of the results of the deterministic YPR analysis with indication of F_{loss} for the Geometric (G) and arithmetic (A) means .

sard_93-10 - Per recruit statistics

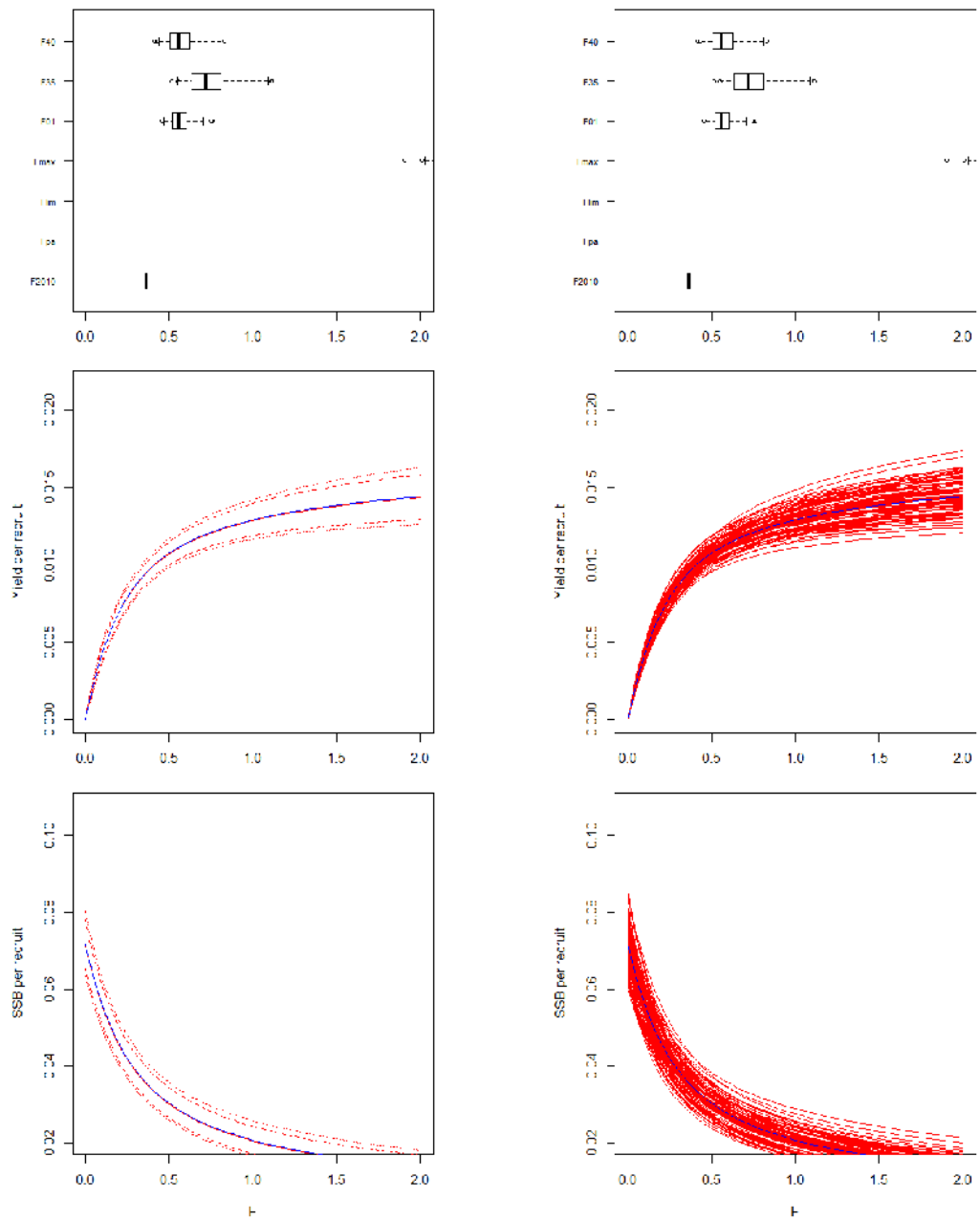


Figure 3.3 – Yield and biomass per recruit curves from plotMSY analysis.

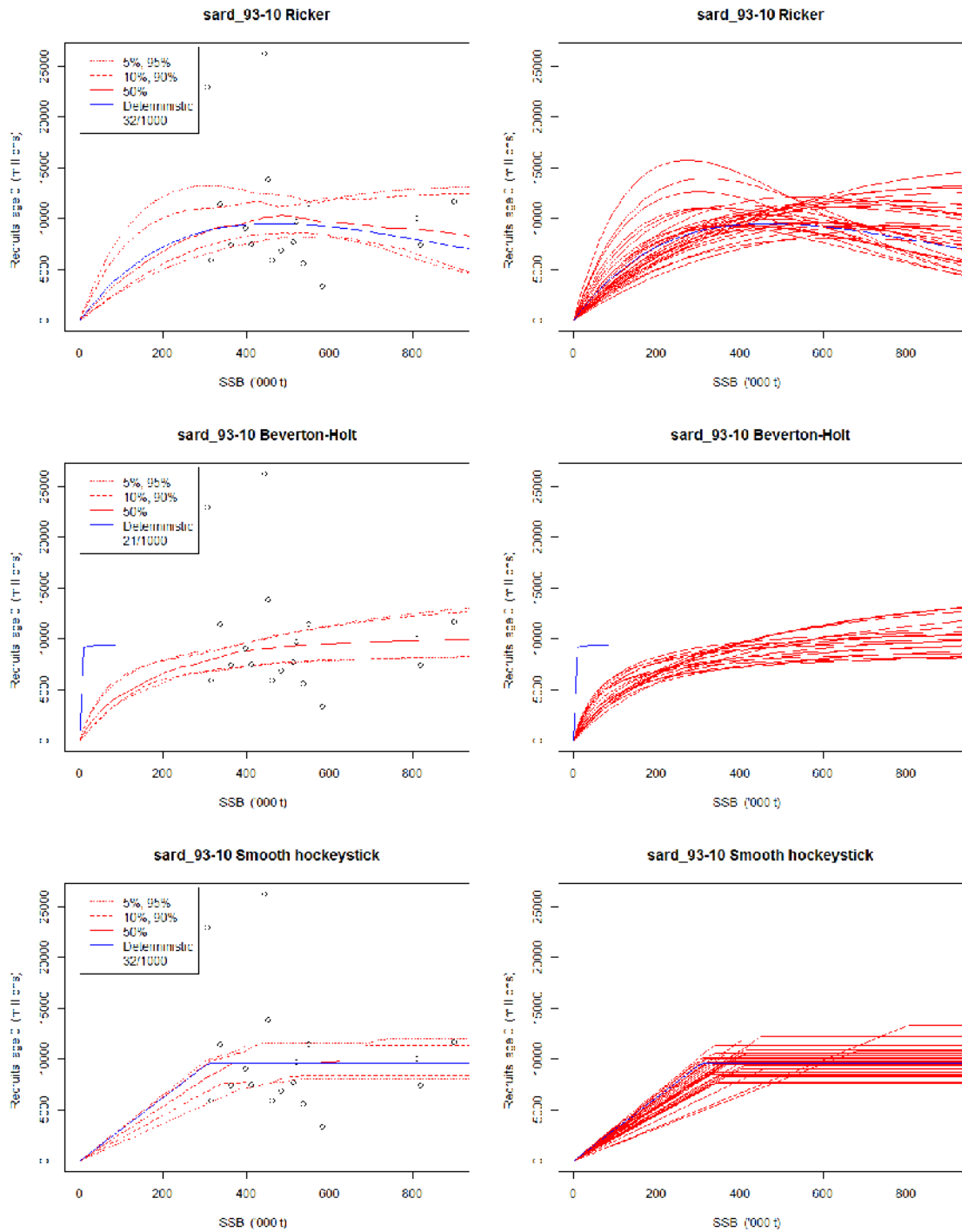


Figure 3.4 – Fit of the three common stock recruitment models to data from 1993-2010 (low recruitment scenario) in the plotMSY analysis.

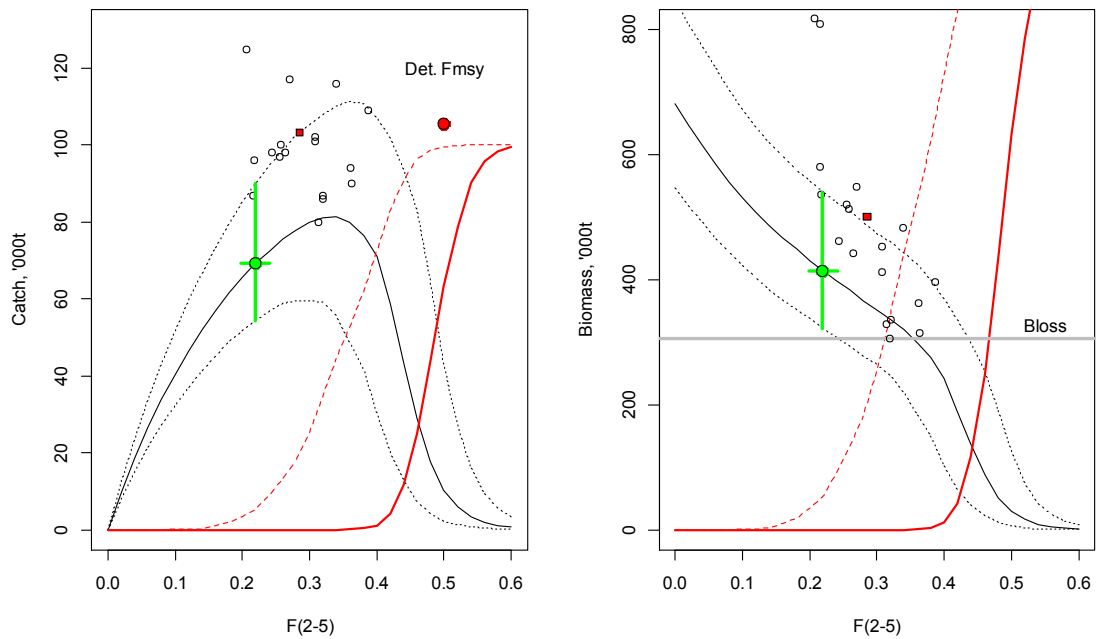


Figure 3.5- Equilibrium yield and biomass for the base case scenario (Case1a) from the stochastic YPR analysis with HCS. The continuous red line is the probability of crashing the stock. The dashed red line is the risk that $B1+ < Bloss$. The green dot shows the fishing mortality that corresponds to a risk of $B1+ < Bloss$ lower than 5% under equilibrium conditions (F_{PSY}), and corresponding yield ($Yield_{PSY}$) and biomass ($B1+_{PSY}$). The green lines are 10% and 90% percentiles of the previous values. The circles are historical values of fishing mortality, catch and biomass in 1993-2010 (mean value in red). Note: risk values should be read on the y scale, with 100% risk corresponding to 100 on the catch plot and to 1000 on the biomass plot.

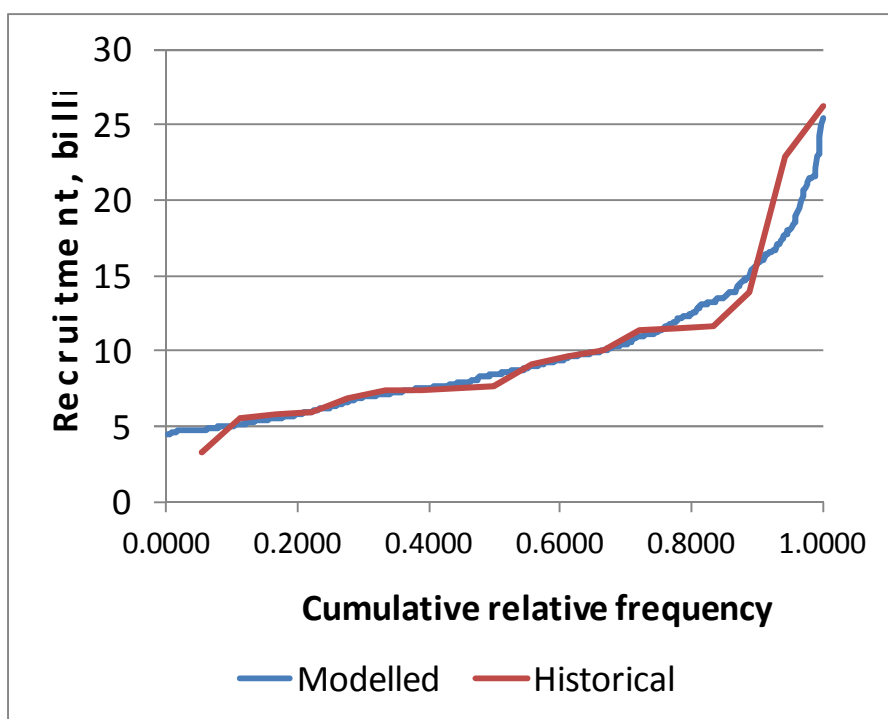


Figure 3.6 – Cumulative frequency of HCS modeled recruitments (low productivity scenario) and historical recruitments in the same period (1993-2010). Modeled recruitments are taken from 500 iterations for B1+>Bloss.

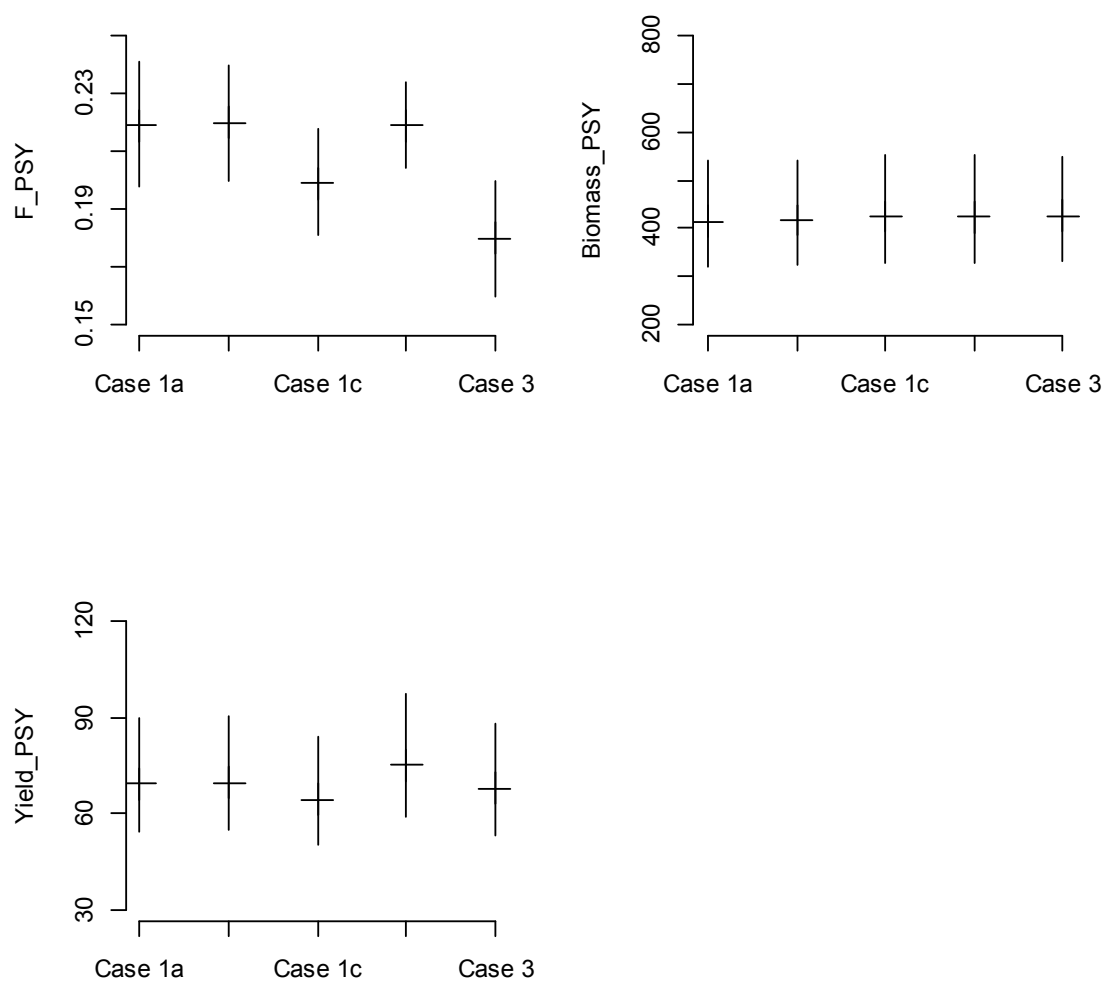


Figure 3.7 – Results of the scenarios (Cases 1-3) explored with HCS13_3. (Top left) Fishing mortality which, with high probability, keeps the stock biomass above Bloss assuming equilibrium conditions ($\text{Prob}(B1 + < \text{Bloss}) < 5\%$) and corresponding biomass (Top right) and Yield (Bottom left). The 10%, 50% and 90% percentiles are shown.

ANNEX 1: SUMMARY OF THE INFORMATION AVAILABLE ON EFFECT OF ENVIRONMENTAL DRIVERS ON IBERIAN SARDINE (*Sardina pilchardus*) DYNAMICS

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Abstract

A brief summary is presented on the results of published studies looking at the effects of environmental variables, at local, regional and global scales, on the abundance and landings of sardine (*Sardina pilchardus*) in Iberian Atlantic waters. Information is also presented on the Pacific and South African sardine (*Sardinops sagax*) stocks for comparison. Results from these studies indicate varying degree of success in explaining and predicting abundance and recruitment series using empirical statistical models.

We also summarize the results of climatic and oceanographic studies in the region and examine evidence for regime shifts. Where regime shifts are proposed, we report on the periods identified as representing low (and high) productivity regimes. However, no unequivocal evidence of regime shifts has been found for the main study area. Much as in the case of fitting empirical models to fish abundance series, the perspective may change depending on which environmental or abundance time-series are considered, the length of the time series, and when the study was carried out.

Small pelagic fish such as sardine and anchovy are characterised by wide interannual fluctuations in abundance (see e.g. Lluch-Belda et al., 1989; Schwartzlose et al., 1999 for reviews). This variability has generally been attributed to environment effects on growth and survival of early life stages and, consequently, recruitment. Several mechanisms have been proposed to explain how different spatially and temporally averaged environmental variables could affect juvenile fish. Effects of the environment on adult fitness and therefore egg production, and on hatching success, have received less attention. It is not clear that recruitment variability is markedly higher in small pelagic fish than in other fish populations. However, in short-lived species, such as many small pelagic fish, recruitment assumes a more important role in population dynamics due to the small number of adult generations and hence less buffering against effects of recruitment fluctuation.

Due to the complexity of marine processes, many hypotheses are possible to explain how the environment could affect fish recruitment (or population variability generally). These range from ideas based on the properties at water column at short temporal scales (e.g. Stable Ocean Hypothesis; Lasker, 1975), meso-scale features (e.g. Optimal Environmental Window Hypothesis; Cury and Roy, 1998) and phenological processes (e.g. Match/Mismatch Hypothesis; Cushing, 1990), to theories based on ocean-scale long-term climatic modes of variability (e.g. Chavez et al., 2003). Proving or disproving any of these hypotheses requires an understanding of the underlying mechanisms. In addition, it is important to take into account the possible effect of biological and ecological factors such as the interactions with other species sharing the ecosystem (including humans).

In the case of the European sardine *Sardina pilchardus* (Waulbaum, 1792), the recruitment series for the Iberian Atlantic shows such fluctuations (Fig. 1) and, in the past, the periodic scarcity of fish, related to successive periods of poor recruitment, resulted in crises for both the fishery and the associated industries due to the socioeconomic repercussions (see Wyatt and Porteiro, 2002 for a review).

Based on the general “fish recruitment” hypothesis mentioned above, there have been several attempts to construct empirical models, using environmental variables at large and local spatial scales, and at temporal scales related to the stock spawning period, to try to explain sardine recruitment variability (e.g. Dickson et al., 1988; Guisande et al., 2001, 2004; Carrera & Porteiro, 2003; Cabanas et al., 2007; Pérez et al., 2010). These studies, summarised in Table 1, obtained mixed results in terms of their ability to predict recruitment, which we argue was due, at least in part, to data issues (e.g. short time series, autocorrelated data, collinearity between putative explanatory variables and the existence of non-linear relationships; Santos et al., 2012) and the varying ability of the methodology applied, to surmount such issues. For example, Borges et al. (2013) refer to the importance of quasi-decadal variability in climatic, oceanographic and fish time-series but where only a few decades over data are available, such cycles are difficult to detect with any certainty. In addition, in all exploited fish populations, it can be difficult to disentangle effects of fishing from those of the environment, especially when only short time-series are available.

Models based on empirical relationships between different time-series always require validation of their predictive power since, especially with short-times series, apparent relationships may be coincidental (e.g. Solow, 2002). While this obviously highlights the need for understanding of underlying mechanisms, the potential value of using environmental relationships in an otherwise unpredictable system should not be underestimated.

Environmental relationships may be strongest at the edge of a species’ distribution, where the species is also at the edge of its realised niche (Myers, 1998). Unless this range limit is due to competitive exclusion by other species, environmental conditions may be at the limits of tolerance for the species and changes in such conditions can thus be critical for survival. Nevertheless, within the distribution range, some areas are likely to be more favourable than others and, when this depends on oceanographic conditions, clearly the location and extent of optimal habitat may change over time.

Have there been regime shifts in the study area?

Environmental conditions show several different modes of variability, including random and cyclic patterns, directional change (such as global warming) and shifts from one stable state via unstable dynamics to a different stable state (i.e. “regime shifts”). Niche theory suggests that directional environmental change and regime shifts may cause a region to become unsuitable for some species, resulting in changes in species’ ranges and/or changes in community composition.

There have been several studies analysing the time series of oceanographic and climatic variables available. In northern Spain, Bode et al. (2012) summarised the results of a multidisciplinary study looking for evidence of the influence of climate change on the oceanography and plankton in the

area using systematic observations collected by the IEO over several decades. Results indicated that there have been significant increases of temperature and a general decrease of precipitation and upwelling intensity, but that these changes “*were not uniform nor homogeneous through the region*”. Sea water level and sea water temperature show positive trends over the time series but no regional long-term trends were apparent for the abundance of different phytoplankton groups, phytoplankton biomass or abundance and biomass of zooplankton.

It has also been proposed that meso-scale and local phenomena in this region strongly interact with large-scale climate and oceanographic processes and that this could explain the variability in the ecosystem responses identified and in the interactions between the non-living and living components of the ecosystem (Bode et al., 2012).

For instance, in Portugal, Lemos and Pires (2004) propose a weakening of the upwelling along the coast and an increase of both offshore and coastal SST since the 1940s. The increase in the SST of coastal waters was subsequently supported by another study (Lemos and Sansó, 2006) which also highlighted an increase in the stratification of coastal waters off Portugal. This warming trend (in SST) was not however homogeneous, and significant spatial differences were found within the study area for the period 1985–2008 (Relvas et al., 2009), revealing the complexity of the oceanography in the region. As was the case for the NW Iberian shelf, where the dynamics of the upwelling (Pardo et al., 2010) and their effect on biological production are not homogeneous (e.g. Pérez et al., 2010; Bode et al., 2011), the superimposition of meso-scale processes on larger-scale variability can obscure the underlying processes and hence limit our understanding of the functioning of the ecosystem in the area (Relvas et al., 2007).

Conclusion:

There is little or no unequivocal evidence of a clear regime shift, i.e. a switch between different stable system states, at least at a regional scale. When shifts have been proposed for the study region or adjacent regions (i.e. Borges et al., 2003 in western Iberian waters; Hemery et al., 2008 in the Bay of Biscay), the breaks identified in the time series do not always coincide with those identified in other studies. Much as in the case of fitting empirical models, the perspective may change depending on which time series are considered, the length of the time series, and when the study was carried out. In addition, the human predisposition to divide the world into categories sometimes leads to imposition of artificial divisions on what is in reality a continuum.

Stock recruitment relationships and reference points for other sardine stocks

Sardine species (Japanese sardine (*Sardinops melanosticus*), South African sardine (*Sardinops sagax*), etc.) are one of the main small pelagic fish resources in eastern boundary upwelling systems. These populations are valuable and highly variable, characterized for the unpredictable dynamics of recruitment.

For this reason, despite a great effort has been devoted to the study of the stock recruitment relationships in these stocks (including studies that takes into account the effect of

environmental variables, etc.(Galindo Cortes *et al.*, 2010, McClatchie *et al.*, 2010)) results are not conclusive (Wada and Jacobson,1998; Sakuramoto, 2012) and a variety of management options have been proposed.

Several analyses carried out for the Pacific sardine (*Sardinops sagax*) have proposed relationships between the strength of the recruitment and SST (Lindgren and Checkley, 2013), upwelling (Ryckaczewski and Checkley, 2008), current strength (Maccall, 2004) and indices such as the Pacific Decadal Oscillation of basin wide scale (e.g. Zwolinski and Demer, 2012). However, McClatchie *et al.* (2010), in contrast to some earlier studies cited therein, found no relationship with SST.

As in the case of other sardine stocks, fluctuations in biomass and shifts in distribution of South African sardine (*Sardinops sagax*) have also been attributed to environmental drivers coupled with overfishing (e.g. Coetzee *et al.*, 2008). For the South African Pelagic Fishery and Pacific Sardine Fishery, operational targets and decision rules are based around the outputs of age- structured models that use survey data and other information to generate estimates of 1+ biomass. In the Western Australian fisheries, the stocks are recovering from substantial declines in abundance, and the decision rules indicate that exploitation rates should not exceed 20% of the spawning biomass (Cochrane 1999; Gaughan and Leary 2005a, b).

The South Australian Sardine stock assessment considered that the recommendations of Smith *et al.* (2011) (bearing in mind that the yields from productive species such as sardine should be typically reduced at depletion levels below 60%) are too conservative for this stock and the 40% of unfished biomass was considered appropriate (Ward *et al.* 2012).

For the assessment of the Japanese sardine Nishida *et al.* 2007 have used three reference points: two for biomass (B_{ban} and B_{lim}) and one for fishing mortality (F_{lim}); F_{lim} sets the maximum F allowed; B_{lim} acts as a threshold below which F decreases linearly until B_{ban} is reached, where the fishery is closed and F becomes zero (Hurtado-Ferro *et al.*, 2010).

In other minor stocks as the South Alboran sardine (*Sardina pilchardus*), the level of exploitation is determined by analyzing the curve of yield per recruit and the calculation of biological reference points F_{0.1} (FAO, 2011).

Role of sardine as a forage species in the ecosystem

There is considerable debate about whether the dynamics of marine ecosystems typically involve top-down, bottom-up or wasp-waist control. Cury *et al.* (2003) suggested that bottom-up control predominates in marine ecosystems, while top-down control plays a role in dampening ecosystem-level fluctuations and wasp-waist control is most probable in upwelling systems. A recent ecosystem model of Bay of Biscay waters (Lassalle *et al.*, 2011) revealed that the continental shelf food web was strongly bottom-up controlled.

Sardine has been described as important in the diet of common dolphin (*Delphinus delphis*) in Portugal (Silva, 1999) and is also present in the diet of this species in Galician waters (Santos et al., in Press). It also occurs in the diet of bottlenose dolphins and harbour porpoises (Santos et al., 2007; Read et al., 2012) and is probably eaten by several other cetacean species. Sardine has been found also in the diet of tunas (Goñi et al., 2011) and of several other fish species, e.g. hake, anglerfish (Preciado et al., 2008).

Small, shoaling pelagic fish species such as sardine, have a higher energetic content than most other available prey and it is expected that a predator should normally “prefer” to eat these species, thereby maximizing its rate of energy intake – this is a basic tenet of optimal foraging theory (Charnov, 1976, Pyke et al 1977).

It has been suggested that common dolphins exhibit an apparent preference for sardine and anchovy (termed “fatty” species) (e.g. Meynier et al. 2008; Spitz et al., 2010). However, a recent analysis based on stomach contents data from stranded common dolphins in Galicia (Santos et al., In press) showed that the relationships between common dolphin diet and annual indices of sardine, hake and blue whiting abundance did not show clear evidence for selective predation on sardine. However, the authors pointed out that lack of evidence for selective predation on energy-rich sardine could be due to current low stock levels. An ongoing analysis suggested that the common dolphins diet in Portuguese continental has changed in response to changes in the pelagic fish community, particularly the decline of sardine and the increase of chub mackerel (Marçalo et al, 2013).

To be able to quantify the role of sardine as a forage species in the Iberian Atlantic ecosystem, we need an ecosystem model that would allow the inclusion of sardine, its predators, its prey and its competitors. For example, Sánchez & Olaso (2004) published an ECOPATH with Ecosim (EwE) model of the Cantabrian Sea. The model included fisheries, although marine mammals and seabirds were not included. More recently, Lassalle et al. (2011, 2012) developed an EwE model for the Bay of Biscay to examine the likely effect of changes in fishing pressure on top predator populations. Creation of such a model for the Iberian Atlantic ecosystem would permit the evaluation of the ecosystem effects of fishing for sardine and any proposed regulatory measures.

References:

- Bode, A., Anadón, R., Morán, X. A. G., Nogueira, E., Teira, E. and Varela, M., 2011. Decadal variability in chlorophyll and primary production off nw Spain. *Climate Research*, 48: 293-305.
- Bode, A., Lavín, A. and Valdés, L. (eds), 2012. Cambio climático y oceanográfico en el Atlántico del norte de España. Temas de Oceanografía. Nº 5., Madrid, Instituto español de oceanografía, 280 pp. ISBN: 978-84-95877-08-6.
- Borges, M.F. (ed), 2013. ICES/GLOBEC workshop on long-term variability in southwestern Europe. ICES Cooperative Research Report, Nº 316, 55. pp.
- Borges, M.F., Santos, A.M.P., Crato, N., Mendes, H., and Mota, B., 2003. Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions. *Scientia Marina*, 67: 235–244.
- Cabanias, J.M., Porteiro, C. & Carrera, P., 2007. The effect of environmental changes in the NE Atlantic sardine fishery. Annex 6, ICES CM 2007/ACFM: 25. 10 pp.

- Carrera, P. and Porteiro, C. 2003. Stock dynamic of the Iberian sardine (*Sardina pilchardus*, W.) and its implication on the fishery off Galicia (NW Spain). *Scientia Marina*, 67 (Suppl.1): 245–258.
- Charnov, E.L., 1976. Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, 9: 129–136.
- Chavez, F.P., Ryan, J., Lluch-Cota, S.E., and Niquen, M.C. 2003. Climate: From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science*, 299: 217–219.
- Cochrane, K.L. (1999). Review of the Western Australian sardine fishery 12–16 April 1999. Report to Fisheries WA. Fisheries Management Paper No. 129
- Coetzee, J.C., van der Lingen, C.D., Hutchings, L., and Fairweather, T.P., 2008. Has the fishery contributed to a major shift in the distribution of South African sardine? *ICES Journal of Marine Science*, 65: 1676–1688.
- Cury, P., and Roy, C. 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. *Canadian Journal of Fisheries and Aquatic Sciences*, 46: 670–680.
- Cury, P., Shannon, L. & Shin, Y.J., 2003. The functioning of marine ecosystems. In: Sinclair, M., Valdimarsson, G. (eds.), *Responsible fisheries in the marine ecosystem*. CABI Publishing, Wallingford.
- Cushing, D.H. 1990. Plankton production and year -class strength in fish populations: an update of the match/mismatch hypothesis. *Advances in Marine Biology*, 26: 249–293.
- Dickson, R.R., Kelly, P.M., Colebrook, J.M., Wooster, W.S., and Cushing, D.H. 1988. North winds and production in the eastern North Atlantic. *Journal of Plankton Research*, 10:151–169.
- FAO, 2011. Report of the Working Group on Stock Assessment of Small Pelagic Species. FAO-GFCM Chania, Crete (Greece) 24–29 October 2011. 2011 FAO
- Guisande, C., Cabanas, J.M., Vergara, A.R., and Riveiro, I. 2001. Effect of climate on recruitment success of Atlantic Iberian sardine *Sardina pilchardus*. *Marine Ecology Progress Series*, 223: 243–250.
- Guisande, C., Vergara, A.R., Riveiro, I., and Cabanas, J.M. 2004. Climate change and abundance of the Atlantic Iberian sardine (*Sardina pilchardus*). *Fisheries Oceanography*, 13: 91–101.
- Goñi, N., Peninon, V., Arrizabalaga, H. & Uriarte, A., 2011. Spatial and temporal variation of anchovy predation by albacore and bluefin tuna in the Bay of Biscay. *ICES CM 2011/L:04*, 13 pp.
- Hemery, G., D'amico, F., Castege, I., Dupont, B., D'elbee, J., Lalanne, Y. and Mouches, C. 2008. Detecting the impact of oceanic-climatic changes on marine ecosystems using a multivariate index: The case of the Bay of Biscay (North Atlantic-European ocean). *Global Change Biology*, 14: 27–38.
- Lassalle, G., Lobry, J., Le Loc'h, F., Bustamante, P., Certain, G., Delmas, D., Dupuy, C., et al. 2011. Lower trophic levels and detrital biomass control the Bay of Biscay continental shelf food web: implications for ecosystem management. *Progress in Oceanography*, 56: 61–75.
- Lassalle, G., Gascuel, D., Le Loc'h, F., Lobry, J., Pierce, G. J., Ridoux, V., Santos, M.B., Spitz, J. & Niquil, N., 2012. An ecosystem approach for the assessment of fisheries impacts on marine top predators: the Bay of Biscay case study. *ICES Journal of Marine Science*, doi:10.1093/icesjms/fss049.
- Lasker, R. 1975. Field criteria for survival of anchovy larvae: The relation between inshore chlorophyll maximum layers and successful first feeding. *Fishery Bulletin*, 73: 453–462.
- Lemos, R.T. and Pires, H.O., 2004. The upwelling regime off the west Portuguese coast, 1941–2000. *International Journal of Climatology*, 24: 511 – 524.

- Lemos, R.T. and Sansó, B., 2006. Spatio-temporal variability of ocean temperature in the Portugal Current System. *Journal of Geophysical Research*, 111, No. C4.
- Lluch-Belda, D., Crawford, R.J.M., Kawasaki, T., MacCall, A.D., Parrish, R.H., Schwartzlose, R.A. and Smith, P.E., 1989. World-wide fluctuations of sardine and anchovy stocks: the regime problem. *South African Journal of Marine Science* 8(1), pp. 195-205.
- Marçalo, A., Nicolau, L., Ferreira, . Vingada, J., Silva, A. & Pierce, G.J. 2013. Variability in the diet of common dolphins (*Delphinus delphis*) and prey availability along the Portuguese continental coast. Symposium of the European Cetacean Society, Setúbal, 2013 (Poster).
- McClatchie, S., Goericke, R., Auad, G. and Hill, K., 2010. Re-assessment of the stock–recruit and temperature–recruit relationships for Pacific sardine (*Sardinops sagax*). *Canadian Journal of Fisheries and Aquatic Sciences*, 67: 1782–1790.
- Myers, R. 1998. When do environment–recruitment correlations work? *Reviews in Fish Biology and Fisheries*, 8: 285–305.
- Meynier, L., Pusineri, C., Spitz, J., Santos, M.B., Pierce, G.J. & Ridoux, V., 2008. Intraspecific dietary variation in the short-beaked common dolphin *Delphinus delphis* in the Bay of Biscay: importance of fat fish. *Marine Ecology Progress Series*, 354: 277-287.
- Pérez, F.F., Padín, X.A., Pazos, Y., Gilcoto, M., Cabanas, M., Pardo, P.C., Doval, M.D. and Farina-Busto, L., 2010. Plankton response to weakening of the Iberian coastal upwelling. *Global Change Biology*, 16: 1258-1267.
- Pyke, G.H., Pulliam, H.R. & Charnov, E.L., 1977. Optimal foraging: a selective review of theory and tests. *The Quarterly Review of Biology*, 52: 137 154.
- Preciado, I. Velasco, F., Olaso, I., 2008. The role of pelagic fish as forage for the demersal fish community in the southern Bay of Biscay. *Journal of Marine Systems*, 72: 407-417.
- Read, F., Santos, M.B., González, A.F., López, A., Ferreira, M., Vingada, J. & Pierce, G.J., 2012. Understanding harbour porpoise (*Phocoena phocoena*) and fishery interactions in the north-west Iberian Peninsula. Final Report to ASCOBANS on grant SSFA/ASCOBANS/2010/4.
- Relvas, P., Barton, E.D., Dubert, J., Oliveira, P., Peliz, A., da Silva, J.C.B. and Santos, A.M.P., 2007. Physical oceanography of the western Iberia ecosystem: latest views and challenges. *Progress in Oceanography*, 74: 149–173.
- Relvas, P., Luís, J. and Santos, A.M.P., 2009. Importance of the mesoscale in the decadal changes observed in the northern Canary upwelling system. *Geophysical Research Letters*, 36:
- Santos, A.M.P., Borges, M. F., and Groom, S. 2001. Sardine and horse mackerel recruitment and upwelling off Portugal. *ICES Journal of Marine Science*, 58: 589–596.
- Sanchez, F. & Olaso, I., 2004. Effects of fisheries on the Cantabrian Sea shelf ecosystem. *Ecological Modelling*, 172: 151-174.
- Santos, M.B., González-Quirós, R., Riveiro, I., Cabanas, J.M., Porteiro, C. and Pierce, G.J., 2012. Cycles, trends and residual variation in the Iberian sardine (*Sardina pilchardus*) recruitment series and their relationship with the environment. *ICES Journal of Marine Science*, 69: 739–750.
- Santos, M.B., Fernández, R., López, A., Martínez, J.A. & Pierce, G.J., 2007. Variability in the diet of bottlenose dolphin, *Tursiops truncatus* (Montagu), in Galician waters, NW Spain, 1990-2005. *Journal of the Marine Biological Association of the United Kingdom*, 87: 231-242.
- Santos, M.B., German, I., Correia, D., Read, F.L., Martinez Cedeira, J., Caldas, M., López, A., Velasco, F. & Pierce, G.J., In Press. Long-term variation in common dolphin diet in relation to prey abundance. *Marine Ecology Progress Series*.

- Schwartzlose, R.A., Alheit, J., Bakun, A., Baumgartner, T.R., Cloete, R., Crawford, R.J.M., Fletcher, W.J., Green-Ruiz, Y., Hagen, E., Kawasaki, T., Lluch-Belda, D., Lluch-Cota, S.E., MacCall, A.D., Matsuura, Y., Nevárez-Martínez, M.O., Parrish, R.H., Roy, C., Serra, R., Shust, K.V., Ward, M.N. and Zuzunaga, J.Z., 1999. Worldwide large-scale fluctuations of sardine and anchovy populations. *South African Journal of Marine Science* 21(1), pp. 289-347.
- Solow, A.R., 2002. Fisheries recruitment and the North Atlantic Oscillation. *Fisheries Research*, 52: 295–297.
- Spitz, J., Mourocq, E., Leauté, J.-P., Quéro, J.-C. & Ridoux, V., 2010. Prey selection by the common dolphin: fulfilling high energy requirements with high quality food. *Journal of Experimental Marine Biology and Ecology*, 390: 73-77.
- Wada T., Jacobson L. D. (1998) Regimes and stock–recruitment relationships in Japanese sardine (*Sardinops melanostictus*), 1951–1995. *Canadian Journal of Fisheries and Aquatic Sciences* 1998;55:2455-2463.
- Wyatt, T., and Porteiro, C. 2002. Iberian sardine fisheries: trends and crises. In *Large Marine Ecosystems of the North Atlantic: Changing States and Sustainability*, Large Marine Ecosystems Series vol. 10, pp. 321–338 Ed. by K. Sherman, and H.R. Skjoldal Elsevier Science, Oxford. 464 pp.
- Yatsu A., Watanabe T., Ishida M., Sugisaki H., Jacobson L. D. (2005) Environmental effects on recruitment and productivity of Japanese sardine *Sardinops melanostictus* and chub mackerel *Scomber japonicus* with recommendations for management. *Fisheries Oceanography* 2005;14:263-278.
- Regimes and stock-recruitment relationships in Japanese sardine (*Sardinops melanostictus*), 1951-1995. Tokio Wada, Larry D Jacobson

Figure 1. *Recruitment series for the Iberian sardine stock: two separate periods are proposed (marked with the horizontal coloured lines) before and after 1993.*

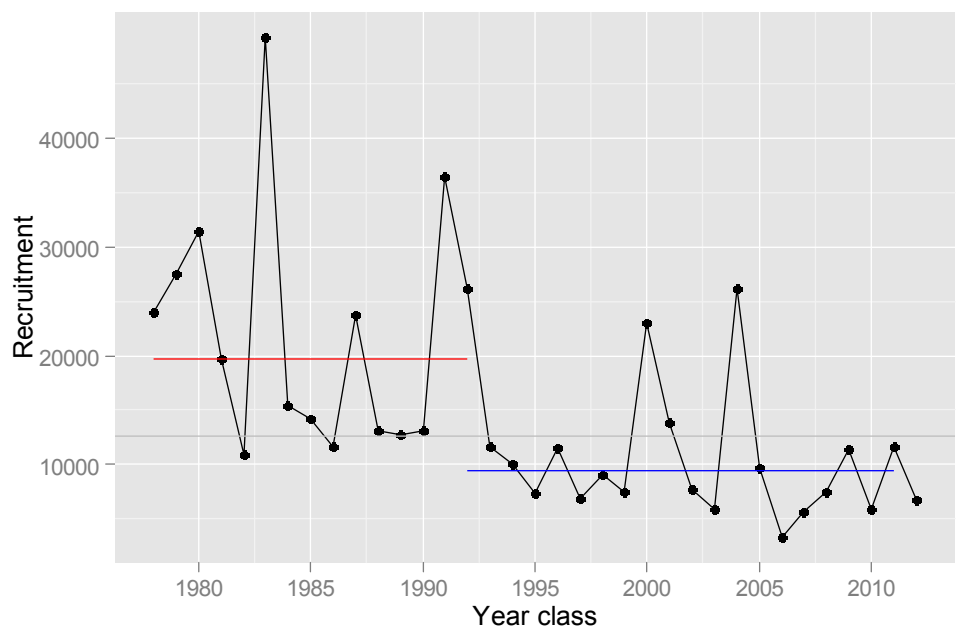


Table 1. *Examples of empirical relationships between Iberian sardine abundance and environmental conditions.*

Scale	Response	Explanatory	Method	Results	Reference
Global and local	Landings of juvenile fish in Vigo (1906-1980)	Sunspot cycle length and the averaged number of sunspots and Ekman transport	Correlations on MC simulations (to avoid autocorrelation)	Sun activity influences water transport that in turn influences R	Guisande et al. 2004
Regional and local	Landings of adult and juvenile fish in Vigo (1906-1980)	Water column stability in February, offshore water transport in March–April, upwelling intensity in the preceding year, and NAO	Definition of an OEW with the explanatory variables using 10-year moving average	Relationships with all the variables (added together to define the OEW)	Guisande et al. 2004
Regional	Sardine landings in IXa (1950-1984)	Average April upwelling index at Porto over the preceding 3 years	Correlation	Relationship highest for the April upwelling index and inverse to catches	Dickson et al. 1988
Regional and local	Portuguese sardine landings (1946-1991)	Wind conditions and NAO	Standard correlation and spectral methods	Periodicity (15 ys) in catch series. Relationships with NAO and wind patterns. Two periods proposed (before and after 1970s)	Borges et al. 2003
Regional and local	Landings of juveniles in Vigo (1980-2000)	NAO winter, upwelling intensity, turbulence, water column stability, larval offshore transport,) and adult abundance	Linear and non-linear regression	Ekman transport and NAO winter	Guisande et al. 2001
Local	R (1976–1998)	Upwelling variability	Linear correlations	For 1987–1992, R at age 0 is positively correlated with the April–September upwelling index. The significant relationship disappears after 1993	Santos et al., 2001
Local	SSB, R and R/SSB (1978–2006)	upwelling index and SST	Multi-oscillatory system approach	Two orbits of stability	Solari et al. 2010
Local	Sardine landings in VIII (1965-2006)	Net Production (calculated using the upwelling index)	Correlations	Explained as decreased upwelling in NW Spain	Pérez et al. 2010

				affects early life stages survival	
Regional and local	R (1978-2007)	Northern hemisphere atmospheric indexes and Ekman transport and wind data	Application of machine learning techniques	Predicted years of low, medium and high R related to mean N Atlantic SST and meridional momentum fluxes across offshore banks	Fernandes et al. 2012 (FACTS report)
Global, regional and local	R and SSB (1978-2011)	Sunspots, northern hemisphere atmospheric indexes, SST, wind strength and upwelling index	Time series decomposition (spectral analysis, GAMs, GAMMs)	<p>Trends in R related to trends in number of sun spots, NAO autumn, winter wind strength and upwelling index</p> <p>Variation around the trend in sardine R related to SST</p>	Santos et al. 2012

Annex 2: Summary of stock-recruitment models fit to sardine using package FLMCore 2.4. Model formulae: Ricker model: $\alpha \cdot B \cdot \exp(-\beta \cdot b)$; Beverton-Holt: $\alpha \cdot B / (\beta + B)$; Segreg: $\text{ifelse}(c(B) \leq \beta, \alpha \cdot B, \alpha \cdot \beta)$. Models were fit to biomass in million tons and recruitment in billion individuals. Comments on autocorrelation, trends and minimization are based on a graphical analysis.

MODEL	Alfa		Beta		Rho		AICc	Derived quantities		Autocorrelation	Trend in residuals	Minimization			Comments
	Value	Std.Error	Value	Std.Error	Value	Std.Error		Rmax (billions)	B1+ at Rmax (million t)			Alfa	Beta	Rho	
Whole period: 1978-2010															
Ricker	59.4	23.7	1.62	0.70			- 10.5	96.279	0.042	Y +	Y -	Clear	Clear		Plausible
Beverton-Holt	15.4	7.1	0.10	0.28			- 10.2			Y +	Y -	Clear	Clear		Density-dependant phase well below observed data
Segmented regression	30.4	3.4	0.44	0.02			- 10.5	13.456	0.442	Y +	Y -	Unclear	Clear		Plausible; breakpoint well above Bloss
Recent period: 1993-2010															
Ricker	55.3	20.7	2.14	0.70			- 10.9	7.006	0.468	N	N	Clear	Clear		Historical data on the right descending limb
Beverton-Holt	6.5	2.0	-0.13	0.09			- 11.5			N	N	Clear	Clear		Not plausible
Segmented regression	31.5	774.9	0.29	7.05			- 10.6	9.029	0.287	N	N	Unclear	Unclear		Plausible
Autoregressive, whole period (1978-2010)															
Ricker Autoregressive(1)	227.3	165.1	4.13	1.27	0.81	0.09	- 18.3	4.820	0.242	Y -	N	Clear	Clear	No min	Historical data on the right descending limb
Beverton-Holt Autoregressive(1)	7.1	2.7	-0.21	0.07	0.76	0.09	- 17.0			Y -	N	Clear	Clear	No min	Not plausible
With evironmental parameters															
Ricker 1978-2011; alfa affected by SST	754.2	282.9	2.10	0.59	-0.06	0.00	- 18.5			Y + (weak)	Y -	Clear	Clear	No min	Plausible
Ricker 1994-2011; alfa affected by SST	558.9	272.4	2.98	0.72	-0.05	0.00	- 11.4			Y + (weak)	Y -	Clear	Clear	No min	Plausible